Functional analysis of stability and variability in multiple forward somersaulting dives from the 3m springboard

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Candidate signature

I, Cherie Anne Walker, hereby declare that this thesis is my own work and does not, to the best of my knowledge, contain material from any other source unless due acknowledgement is made. The thesis was completed under the guidelines set out by The University's Faculty of Health Sciences, for the degree of Doctorate of Philosophy and has not been submitted for a degree or diploma at any other academic institution.

I, Cherie Anne Walker, hereby declare that I was the principal researcher of all work included in this thesis, including work published with multiple authors. An author contribution statement for published work is detailed at the beginning of each relevant chapter.

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ABSTRACT

Springboard diving is a highly complex sport that requires individuals to propel themselves from a compliant surface and perform intricate aerial sequences. Athletes are continuing to push the limits for how many airborne somersault revolutions can be performed while aiming to consistently achieve successful performance outcomes on water entry. Understanding the underlying coordination strategies associated with performing these complex dives is important to implement successful performance strategies. A limitation of the current research on springboard diving is that a majority of the literature it is based upon pre-determined discrete measures collected from group study designs, subsequently reducing the unique features and structures of individual diver's movement patterns. Thus, the overall aim of this body of work was to investigate within-participant variability of springboard divers performing multiple forward somersaulting dives from the 3m springboard.

Water proof inertial measurement units (IMUs) were presented as a novel methodology for collecting continuous time-series data in springboard diving (Chapter 3). A lab based accuracy assessment compared angular velocity output measures of IMUs gyroscopes with a three-dimensional optical tracking system (Cortex 3.3). IMUs were comparable to the optical tracking system with <0.5% difference ($p < 0.05$) between the two system angular velocity data and <1.0% difference when integrating angular velocity to determine change in angular displacement.

Highly skilled springboard divers with the ability to perform multiple somersaulting forward dives from the 3m springboard were recruited. Continuous time-series angular kinematics data were collected from the IMU's gyroscopes and pre-determined discrete measure were determined via high-speed video footage.

Angular velocity time-series plots qualitatively illustrated differences in rotational speeds, change in angular displacement and dive flight duration between the forward 1½ pike, 3½ pike and 4½ tuck somersaults (Chapter 3). Biomechanically, hardest dive currently being performed by divers at competitions (4½ tuck somersaults) differed from lower degree of difficulty dives in terms of: (1) a rotational delay immediately after takeoff (to gain greater vertical translation); (2) increased total time of flight ($p = 0.008$); and (3) generation of greater rotation speeds (1090±7.0deg/s, $p < 0.001$).

Within-participant movement variability reduced as dive degree of difficulty increased for the discrete variables angular displacement and duration of the Initial Flight and Somersault phase. In contrast, variability increased for the Opening phase (Chapter 4). Divers achieved consistent Total Flight angular displacements (0.5-0.9%) by using a feedback control strategy to link and adapt the timing and rate of angular deceleration during the Opening phase.

To more definitively understand underlying coordination strategies and the effect of movement variability during the entire movement sequence of the forward 3½ pike somersault dive, angular velocity time-series data were analysed using functional principal component analysis (*f*PCA). Firstly, differences between the structure and magnitude of variability were analysed according to skill level by combining the repeated measures of the two female divers into a single analysis (Chapter 5). From this analysis, the first five *f*PCs represented 96.5% of variability within the combined angular velocity curves. Scatter plots and standard deviations of *f*PC demonstrated that the International diver had greater consistency in the structure of performance, while the National diver did not present a definitive structure of performance due to a larger magnitude of variability. Secondly, to understand the unique performance characteristic of individual divers, separate *f*PCA were performed for each diver and resulting *f*PC scores were correlated to discrete performance kinematics (Chapter 6). The national diver presented a larger number of correlations that where related to linear kinematics, while the

International diver presented significant correlations that were more related to angular kinematics. These findings highlighted unique areas where performance technique enhancements can be made to improve the success of the forward 3½ pike somersault dive.

Water entry is the final phase of a dive and is a key task constraint. Correlations between dive flight angular kinematics and reported relatively minor variations of Total Flight angular displacement were significantly correlated with the body alignment at the instant of hand, hip and knee water entry (p <0.05) (Chapter 4). *f*PCA also reported significant correlations between a more vertically aligned hand entry posture and higher angular velocity during the Initial Flight and/or Somersault phases (International: *f*PC1 $r = -0.761$, $p < 0.05$; National: *f*PC3 $r = -0.796$, $p < 0.01$) (Chapter 6).

The current body of work showcased the importance and feasibility of within-participant research designs for multiple sporting contexts in understanding the underlying nature, technique and strategies of unique individuals to optimise technique, reduce performance error and improve overall skill.

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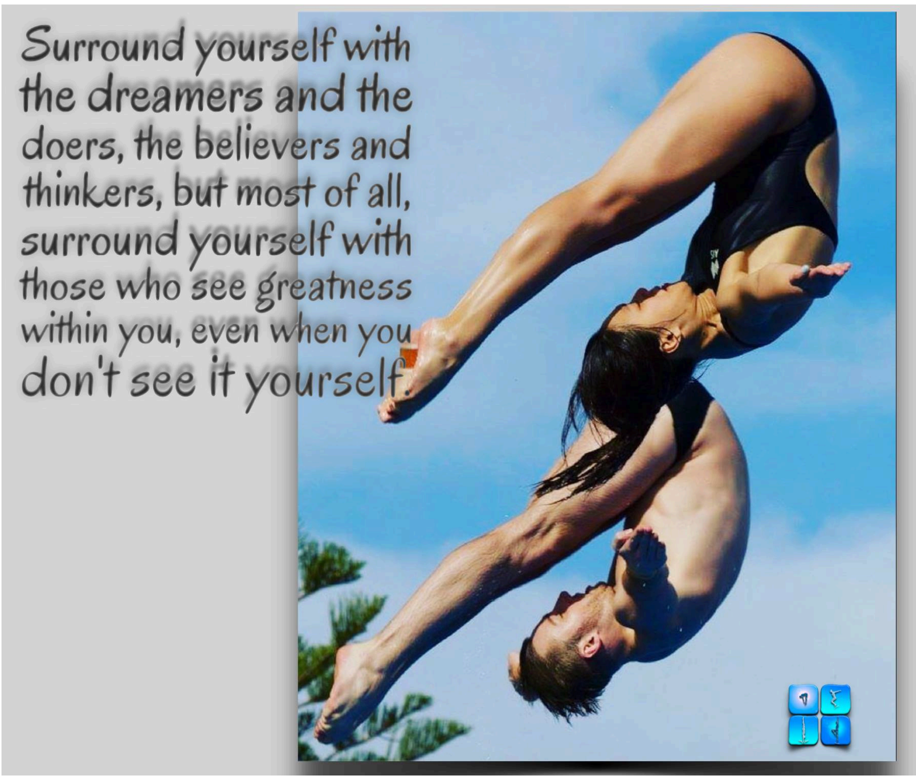

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CHAPTER 1

Introduction and thesis overview

Background

Historically, springboard diving has been an Olympic event since 1908 for men and 1920 for women. To begin with, dives such as the "swan dive" and forward 1½ somersault were performed. Today however, divers from the 3m springboard can now perform somersaulting dives with 3½ (women) or 4½ (men) somersault revolutions before water entry.

During competitions, dives must be performed from each of the five rotational directions: forward, backward, reverse, inward and twisting. For this body of work, we chose to examine the forward dive due to the highest number of somersault revolutions being performed in this category at competitions. To commence a forward dive, a running approach is used, which consists of 3-5 fast steps, followed by a hurdle, maximum springboard depression and takeoff. After takeoff, the initial dive flight begins with the diver folding their body into a tight ball (tuck) or pike (flexed hips and extended knees) somersault position. The diver remains in the somersault position until they have completed the required revolutions. The diver then unfolds (Bardy & Laurent, 1998) from their somersault position by extending their body in preparation for a head first water entry. Once the diver is completely submerged into the water the dive performance is finished and the judges present their scores.

Personal observations of national-level training in Australia exhibited a common goal is expressed by coaches to their athletes. This goal ultimately translates to consistently performing enough rotation to achieve a "ripped entry" (i.e., clean water entry with little to no splash) on every dive. Continuous repetition of such dives in training is the common strategy to improve such performance, and the "practice makes perfect" philosophy is pervasive in the sport context. Based on my initial observation, divers seemed to have their own style when executing repeated performances of their multiple somersaulting dives. However, to date no research has been presented to understand whether and how divers uniquely create their movement sequences for multiple forward somersaulting dives.

The first biomechanical paper analysing springboard diving (to our knowledge) was published in 1940, where basic mechanics were reported outlining how board work, height, rotations and dive distance were achieved (Lanoue, 1940). To measure these kinematic variables, dive performances were projected onto a screen and figures were traced. Ironically, current methodological procedures have not evolved much since; and a majority of biomechanically based springboard diving studies have presented data collected from two-dimensional video footage digitisation (see e.g., Miller (1973) and Barris, Farrow, and Davids (2014)). This method can be time consuming due to the multiple steps required to calculate accurate data, including: (1) calibrating the aquatic venue (Sinclair, Walker, & Rickards, 2012); (2) clearly marking anatomical land marks (Bartlett, Bussey, & Flyger, 2006) and preventing movement of land mark skin artefacts (Forner-Cordero et al., 2008): (3) manual two-dimensional digitisation to collect x and y pixel coordinates; (4) conversion of pixel coordinates to real-world values; and (5) calculation of pre-determined kinematic variables.

While two-dimensional analysis of springboard diving has provided important biomechanical information to coaches and sports scientists, current technological advances, in the form of inertial measurement units (IMUs), present new opportunities to examine springboard diving with innovative procedures. IMUs are micro sensors that can contain three axial gyroscopes, accelerometers and magnetometers, with the ability to measure and capture angular velocity (deg/s), linear acceleration (m/s^2) and magnetic field strength (µT) (Finch, Lintern, Taberner, & Nielsen, 2011). IMUs are becoming an acceptable tool for sports biomechanics (Fitzpatrick & Anderson, 2006), have the ability to provide reliable data (Bergamini et al., 2013) and have advantages over existing methodological tools, such as video, which include real time continuous time-series data and less time constraining data analysis.

As with the first biomechanical paper presented in 1940, the common trend in springboard diving studies have been the use of traditional group study designs, where pre-determined discrete kinematics and kinetics are collected and examined. These designs haven't helped researchers in understanding the capabilities of an individual to successfully perform a dive task. The normalisation of group data conceals participant specific information (Bartlett, Wheat, & Robins, 2007) and the degree of change in the coordination (movement variability) between repeated performances of the same dive (Button, MacLeod, Sanders, & Coleman, 2003). The first series of investigations of springboard diving to step away from pre-determined group kinematics occurred within Barris' (2013) thesis. Movement coordination patterns of the lower-limb were examined throughout the springboard approach with the aim to assess the ability of individual divers to functionally adapt their approach and reduce "baulked" (stopped) dives. This work represented the first attempts to post examine data to determine ecological dynamics and motor control of the springboard approach movement pattern.

The continual movement sequence and repetitive nature of springboard diving also permits the potential utilisation and application of Functional Principal Component Analysis (*f*PCA) to assess repeated attempts of multiple somersaulting dives. Whilst a relatively new analytical technique, *f*PCA has to date been used in several sporting contexts to analyse movement stability and variability in continuous time-series data (Dona, Preatoni, Cobelli, Rodano, & Harrision, 2009; Kipp & Harris, 2015; Ryan, Harrison, & Hayes, 2006; Warmenhoven et al., 2015). The application of *f*PCA into the assessment of dive characteristics and phases of dive flight has not previously occurred. That said, existing studies of gymnasts performing somersault manoeuvres have reported the presence of movement coordination patterns (Bardy & Laurent, 1998; Gittoes, Irwin, Mullineaux, & Kerwin, 2011; King & Yeadon, 2003; Lee, Young, & Rewt, 1992; Yeadon & Hiley, 2014). It is unknown, however, to what extent and how springboard divers coordinate dive flight phases to meet coaching instructions of sufficient rotation and a ripped entry, let alone how coordination changes when the dive task required changes (e.g., somersault revolutions required increase).

Statement of the problem

Biomechanical reports on springboard diving have been limited to two-dimensional video analysis, reflecting a time-consuming manual method of data-analysis to attain accurate data on performance. Consequently, a majority of springboard diving research has been limited to pre-determined discrete measures recorded from a group of divers with minimal repeated measures. A particular limitation within previous research is that data collection has been conducted during competition, subsequently reducing data to one performance trial per individual. Although prior research on discrete characteristics has provided important information on advanced dives, there are limitations with this as a single trial does not allow researchers to determine an individual's ability to adapt to complex tasks and discrete measure analysis sacralises the full data sequence. A large portion of springboard diving research has also focused on the springboard approach, limiting the understanding of what movement strategies are being use during the flight phase of a dive performance. Hence, the general aim of this thesis was to implement new technology in an effort to more proficiently examine and understand the rotational profiles of highly skilled 3m springboard divers.

Specific aims

Aim 1: To determine the accuracy of IMeasureU® water proof inertial measure units (IMUs), with particular reference to the gyroscopes embedded within the model.

Aim 2: To determine the practical application of IMUs to springboard diving by examining a larger number of repeated measures of individual diver's flight phases during forward dives of increasing difficulties.

Aim 3: Examine within-participant movement variability during different phases of dive flight and determine whether increasing dive degree of difficulty affected the level of movement variability displayed.

Aim 4: Examine whether skill level impacts the magnitude (amount) and structure (type) of within-participant movement variability during the dive flight.

Aim 5: Examine the effects of dive flight movement variability (measured by IMUs) on pre-determined discrete kinematics typically measured in previous springboard diving research (measured by two-dimensional video analysis).

Theoretical frame work

The purpose of this body of work was to combine the methods of biomechanical assessment with the theoretical and practical constructs from motor control and learning, in order to better examine and understand individual performance within the context of springboard diving. Some of the fundamental principles of motor control and learning consider that movement is governed by the coordination of multiple degrees of freedom (Bernstein, 1967). Synergies need to be developed to help ensure efficiency in movement coordination and responsiveness to permit adaptability during motor execution (Harbourne & Stergiou, 2009). On this basis, movement variability within well learned tasks can be understood as potentially being functional, helping athletes adapt to complex dynamic tasks, evolving movement and environmental conditions (Bartlett et al., 2007). Understanding the underlying biomechanical control strategies of individual divers is therefore seen as critically important to assess the capabilities of high level springboard divers, and in being able to effectively optimise their skilful performance.

Thesis outline

In accordance with the stipulated aims and theoretical framework, seven chapters in total are presented as follows within this body of work:

Chapter 1: *Introduction and thesis overview*

Provides a background for the reasoning behind this body of work

Chapter 2: *Literature review*

Provides a background for the structure of the succeeding research chapters, in the fields of springboard diving biomechanics, methodology and movement variability.

Chapter 3: *The application of Inertial Measurement Units to springboard diving*

Investigates the accuracy of IMUs with a three-dimensional optical tracking system and presents practically significant information on angular and temporal kinematics as forward dive degree of difficulty increases.

Chapter 4: *Movement variability of springboard divers' flight during multiple forward somersaulting dives*

Examines movement variability of pre-determined discrete kinematics of increasing forward dive degrees of difficulty for individual divers, as well as the effect of movement variability on the performance outcome of entry body alignment.

Chapter 5: *How functional data analysis can help more finitely characterise between and within technical movement variability: Insights from springboard diving*

Investigates the differences between the structure and magnitude of variability in continuous angular velocity time-series for different skill levels (National and International), by combining repeated measures of the forward 3½ pike somersault dive into a single functional principal component analysis (*f*PCA).

Chapter 6: *A continuous times-series and discrete measure analysis of individual divers performing the 3½ pike somersault dive*

Investigates individuals structure and magnitude of angular velocity variability during repeated measures of the forward 3½ pike somersault dive separately for individual divers and correlates these findings the key discrete performance measures.

Chapter 7: *Discussion and thesis conclusion*

Summarises the results of Chapters 2-6, discusses the implications of the findings from the current body of work, outlines directions for future research and presents the final conclusions from results presented in the studies conducted.

Significance of this thesis

This body of work provides information on the accuracy of IMU gyroscopes in measuring angular kinematics of springboard divers and therefore represents the practical application of IMU technology in sport contexts. The procedural and analytical methodologies presented demonstrate opportunities for sporting institutes to move away from the more time-consuming and potentially less accurate two-dimensional analysis technique, to the use of IMUs in sports performance. IMUs permitted the occurrence of repeated dive performances for each individual diver. As a result, unique movement strategies and capabilities for each individual diver were identified and illuminated. Clear implications were drawn from the studies and which will help sports scientists to analyse and interpret individual movement coordination and control strategies, separately and independent to group norm references.

In addition, this body of work is the first to demonstrate the application of functional principal component analysis (*f*PCA) to angular velocity time-series data. Studies presented were able to quantitatively analyse continuous wave-form data and report on the structure and magnitude of movement variability within individual dive performances. Multiple implications can be drawn from the statistical applications of *f*PCA, including examining performance differences according to skill level, individual differences in the movement structure, and the identification of an individual's strengths and weaknesses in constraints (or features) of performance. Overall, this body of work, demonstrates the testing, integration and application of contemporary technology and analysis techniques. These can be applied to multiple sporting contexts for the purpose of better examining and understanding the intricate nature of individual athlete's capabilities in controlling and adjusting technique, as well as reducing movement error and ultimately improving overall skill.

Dissemination of results

At the time of submission, portions of this thesis have been submitted for publication and/or presented as follows:

Journal Publication

Chapter 3: Walker, C., Sinclair, P., Graham, K., & Cobley, S. (2016). The validation and application of inertial measurement units to springboard diving. *Sports Biomechanics*, 1-16. doi:10.1080/14763141.2016.1246596. Accepted 6/10/2016

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Chapter 4 is under review as: Walker, C. A., Sinclair P. J., Cobley S. Movement variability of springboard divers' flight during multiple forward somersaulting dives. *Sports Biomechanics.* Submitted 01/07/2016.

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Walker, C. A., Sinclair, P. J., Graham, K. S., & Cobley, S. (2016). Practical application of IMUs to the sport of Springboard diving. *Paper presented at the High Performance Sports Knowledge Growth Forum,* Australian Institute of Sport, Canberra, ACT, 5 – 7 December.

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Warmenhoven, J., & Walker C. A. (2016). Application of biomechanics to athlete pathways. *Guest presenter at the Australian Institute of Sport Winning Pathways Workshop,* Australia Institute of Sport, Canberra, ACT, 12 – 13 December.

<u>Pilot data collected during the beginning of this thesis was presented as:</u>

Walker, C. A., Sinclair, P. J., Cobley, S., Sanders, R. H., & Graham, K. S. (2014). A comparison of multiple forward somersault dives from the 3m springboard: a case study. In K. Sato, W. A. Sands & S. Mizuguchi (Eds.), *XXXII International Society of Biomechanics in Sports Conference Proceedings* (pp. 353-356). Johnson City, Tennessee, USA: East Tennessee State University, 12–16 July.

Sinclair, P. J., Walker, C. A., & Cobley, S. (2014). Variability and the control of rotation during springboard diving. In K. Sato, W. A. Sands & S. Mizuguchi (Eds.), *XXXII International Society of Biomechanics in Sports Conference Proceedings* (pp. 357-360). Johnson City, Tennessee, USA: East Tennessee State University, 12–16 July.

Walker, C. A., Sinclair, P. J., & Cobley, S. (2015). Kinematics analysis of the backward 2.5 somersaults with 1.5 twists dive (5253B) from the 3m springboard In F. Colloud, M. Domalain, T. Monnet, S. Boyer, H. Noël & S. Guérineau-Brion (Eds.), *XXXIII International Society of Biomechanics in Sports Conference Proceedings* (pp. 1051-1054). Poitiers, France: University of Poitiers, 29 July - 3 August.

Grant applications

Data collected throughout this thesis was used for the application and development of the 'somersault frame':

Graham, K. S., Walker, C. A., Sobrino, C., & Rodriguez, J. (2014). Research into Action Fund. NSW Institute of Sport. Australian Sports Commission

CHAPTER 2

Review of literature

Background

Springboard diving is an internationally recognised sport that requires athletes to jump from a compliant surface, propelling themselves into the air while executing complex aerial movements before entering the water. Understanding the key kinematics during the dive and a diver's ability to cope with variations within a movement patterns is important to understand how a successful dive is achieved.

To address movement variability and the kinematics of a successful dive, this review is divided into three sections. The first section introduces theories on movement variability, constraints and statistical analysis techniques. The second section reviews the existing biomechanical research analysing springboard diving, with a particular focus on the methodology of data collection. Finally, the third section combines the theories of movement variability with relevant sports relating to springboard diving.

Movement variability

Variability is considered to be changeability of a system. It is a natural feature of the behaviour of organisms, with no two movement patterns being identical (Newell & Slifkin, 1998). Movement variability can be defined as the degree of change in coordination patterns between trials/attempts of the same movement sequence (Button et al., 2003). In the existing literature there are two theories predominately discussed in regards to movement variability; the control theory (traditional view) and dynamical systems theory.

Control theory

Traditionally, movement variability was considered to be random fluctuations within the biological movement system (e.g. anatomical, mechanical, physiological) (Davids, Glazier, Araújo, & Bartlett, 2003; Glazier, Wheat, & Bartlett, 2006). Variability was viewed as a concept of error where the motor system is unable to organise the multiple degrees of freedom available to make a final output signal for a planned movement pattern (Preatoni, Ferrario, Dona, Hamill, & Rodano, 2010). Movement pattern output measures were understood as a signal and its noise (Newell & Slifkin, 1998). Traditionally within-participant variability was seen as a reflection of noise caused by the fluctuations in the sensomotor system (Newell & Corcos, 1993). These fluctuations were seen as being detrimental to normal function and sports performance (Bradshaw, Maulder, & Keogh, 2007; Emmerik & Wegen, 2000; Gittoes et al., 2011; Langdown, Bridge, & Li, 2012; Wilson, Simpson, Van Emmerik, & Hamill, 2008).

Traditional sports biomechanics believed that there was an optimal pattern for movement sequences, leading to normative values that determine optimal sports performance (Bartlett et al., 2007; Brisson & Alain, 1996; Schöllhorn & Hans, 1998). Brisson and Alain (1996) tested this theory by examining participants performing a bat-ball task. Two training templates were prescribed; 1) the "optimal" kinematic pattern determined from the best performer and 2) individual's movement pattern determined from each individual's best performance. The performance of the skill increased and outcome variability reduced when participants used their own personal best kinematic pattern. Kinematic patterns are produced by coordination between local structures, and variability of these structures (local variability) can reduce the outcome variability (global variability) (Hamill et al., 1999; Wilson et al., 2008). Brisson and Alain (1996) concluded that there was no optimal coordination pattern as morphological and physical constraints (e.g. muscular strength, power, speed and limb length) can affect subjects' kinematics in different ways and that many different patterns can be used to produce the same task. The existence of a common motor pattern is now considered to be a misconception, with no two movements being identical (Bartlett et al., 2007; Brisson & Alain, 1996; Davids et al., 2003; Glazier, Davids, & Bartlett, 2003; Newell & Slifkin, 1998).

Dynamical systems theory

A contemporary approach interpreting athletic performance is the dynamical systems theory, which accentuates the process of coordination and control within the human movement system. This theory considers the movement system as a highly intricate network of co-dependent subsystems (e.g. skeletomuscular system) that are composed of a larger number of interacting components (e.g. muscles tissues) (Glazier et al., 2003). The coordination of the separate elements of an athlete's sub-systems facilitates homogeneity, integration and structural unity within a movement pattern (Bernstein, 1967, p. 30). Bernstein (1967, p. 127) defined the coordination of movement as the process of mastering the redundant degrees of freedom in a system that cannot be regarded as an independent activity but as a means of ensuring responsiveness and flexibility of execution in the motor system.

The dynamical systems theory considers variability to be essential within and between all biological systems (Newell & Corcos, 1993), with no single causal role being assigned to specific subsystems when creating movement (Williams, Davids, & Williams, 1999, p. 257). The complexity of the movement system is reflected by its nonlinear changes within the subsystems, resulting in flexible movement patterns (Harbourne & Stergiou, 2009). Variability within a movement system is now seen as a functional adaptation to the perturbations during the performance of a skill (Bartlett, 2008; Bartlett et al., 2007; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Langdown et al., 2012; Newell & Slifkin, 1998; Wilson et al., 2008), with a current trend for sports biomechanists analysing variability to follow the dynamical systems theory (Bradshaw et al., 2007; Gittoes et al., 2011; Hiley, Zuevsky, & Yeadon, 2013; Langdown et al., 2012; Preatoni, 2010; Trezise, Bartlett, & Bussey, 2011; Wilson et al., 2008).

Constraints

The performance of a skill is governed by the multifactorial integration of variables based around the physical aptitudes, task demands and environmental elements (Glazier, 2015). Whether a coordination pattern is highly consistent or manipulated is determined by the constraints imposed on the task at hand. A constraint is considered to be a boundary or feature that limits the number of possible degrees of freedom available to an individual (Newell, 1986). Newell's dynamical model implies that the human body produces different coordination patterns due to the impositions of the organismic, environmental and task constraints acting upon them (Figure 1), with acrobatic sports being highly constrained by task specific coordination patterns (Newell, 1985).

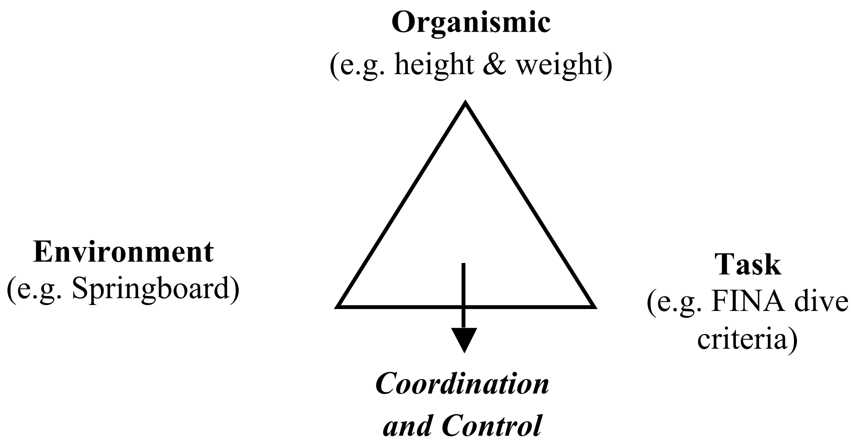

Figure 1. Schematic of the constraints that specify the optimal patterns of coordination and control adapted from Newell (1986). The examples listed in the parenthesis are related to springboard diving.

Organismic constraints

The organismic constraint relates to the structural and functional constraints of the human body. These include body weight, height, shape, muscular strength and power. Individuals have their own unique organismic constraints that will affect their ability to interact with the environment and task constraints (Newell, 1986). The most influential organismic constraint for springboard diving is the growth of young athletes. As junior athletes begin to grow, changes to the absolute and relative size of their body parts will have an overall impact of the biomechanical proficiency of the system (Newell, 1986). The most important and influential variable for a diver is the change to their mass moment of inertia, which will ultimately affect their rotational abilities (Mikl, 2014). To illustrate such changes, Jensen (1981) examined the changes to mass moment of inertia during childhood. The study analysed the changes in the moment of inertia of 4-12 year olds over a 12 month period. Mean increases of 30.8% about the transverse axis and 33.5% about the longitudinal axis were recorded. Changes in body size and shape will cause an increase in the resistance to aerial rotation. These changes need to be matched by increases in strength, to allow a diver to perform the same skill with the appropriate coordination and control required (Newell, 1986).

Environmental constraints

Environmental constraints are ones that are external to the organism. These constraints include gravity, ambient temperature, natural light, location, visual and auditory information (Handford, Davids, Benneth, & Button, 1997; Newell, 1986). In springboard diving an athlete needs to be able to cope with different environmental variables when travelling to competitions, such as weather extremes in outdoor facilities, visual cues for spotting and the springboard provided at competition.

Task constraints

Task constraints specify the kinematic or dynamic nature of the response that an athlete is able to perform (Newell, 1986). Diving can be considered a closed sporting skill (Highlen & Bennett, 1983), where the rules and goals of the sport specify the specific patterns of coordination required for the movement phase or skill (Newell, 1985). The Fédération

Internationale de Natation (FINA) specifies the nature of how dives should be performed, providing judges with an execution criterion for dive scores (Appendix 1). It must be noted that individuals may interpret the task specific requirements differently, and therefore investigators may see a variety of coordination patterns when producing the same task (Newell, 1986).

Springboard divers are required to interconnect the network of constraints that are imposed on them, with variability being proposed to provide the movement system with ability to adapt to the complex dynamic tasks and environmental constraints in order to produce intricate aerial manoeuvres (Bradshaw et al., 2007; Davids & Button, 2004; Trezise et al., 2011).

Skill level and within-participant variability

The traditional motor learning perspective believes that, as skill level increases, variability decreases (Glazier et al., 2006). However, the common trend in the literature supports the dynamical systems perspective that expert athletes' movement variability does not decrease as skill level increases, but instead is utilised to permit adaptation to perturbations in the constraints acting upon them (Anderson, Breen, & Tucker, 2008; Bartlett, 2008; Burgess-Limerick, Abernethy, & Neal, 1991; Button et al., 2003; Davids et al., 2003; Phillips, Portus, Davids, & Renshaw, 2012; Preatoni, 2010; Schorer, Baker, Fath, & Jaitner, 2007; Wagner, Pfusterschmied, Klous, von Duvillard, & Müllera, 2012; Wilson et al., 2008). An athlete's skill level (novice, advance and expert) has been associated with a U-shaped curve for the level of movement variability (Bartlett, 2008; Schorer et al., 2007; Wilson et al., 2008). Novice athletes tend to experience higher random variability, as they search for appropriate movement coordination patterns (Button et al., 2003) within a restricted number of degrees of freedom (Bernstein, 1967). Intermediate athletes experience a period of stability, where further practice will lead to a reduction in unwanted negative variability (Wilson, Simpson, Hamill, & Emmerik, 2007). In order to develop a highly functional control strategy skilled athletes unlock the degrees of freedom available to the system leading to a greater economy of movement (Bernstein, 1967). As an expert athlete develops, functional adaptations to perturbations in movement patterns develop and the variability seen in movement patterns increases again (Arutyunyan, Gurfinkel, & Mirskii, 1968; Schorer et al., 2007; Wilson et al., 2008).

Contrastingly, a study analysing gymnasts' ability to perform multiple giant swing circles on the high bar observed high level elite gymnasts to be more precise in their timings of the mechanically important aspects of their downswing (instant of maximum extension and flexion during the downswing) than less elite gymnasts, but presented with higher variability in the less important aspects (Hiley et al., 2013). The higher variability during the less important aspects was associated with a control feedback strategy to ensure less variability during the mechanically important aspects of the movement pattern. Similarly, more experienced baseballers had less variability during the kinematic motions of pitching task (Fleisig, Chu, Weber, & Andrews, 2009) and more experienced basketball players had less joint space variability during a free throw, increasing functional precision (Button et al., 2003).

Whether variability is going to increase or decrease as skill level develops will depend on the task at hand; movement that requires high precision may be associated with a decrease in variability during key elements (Bardy & Laurent, 1998; Fleisig et al., 2009; Hiley et al., 2013), but movements that require adaptation to unexpected constraints may result in increased variability in more skilled performers (Burgess-Limerick et al., 1991; Hamill et al., 1999; Komar, Seifert, & Thouvarecq, 2015; Schorer et al., 2007; Wilson et al., 2008).

Measuring variability

The dynamical systems approach assesses the individual's ability to perform a complex skill. The same performance outcome can be achieved using many different techniques, with inherent variability permitting flexibility within a skill. Thus the analysis of a single trial in human movement is not appropriate as assumptions from a single performance measure cannot determine an individual's ability to adapt to complex dynamic tasks and environments (Gervais & Dunn, 2003; Mullineaux, Bartlett, & Bennett, 2001). The importance of understanding an individual's strategy when performing a skill is highlighted in the following quotation from Dona et al. (2009, p. 285)

> *"When trying to capture the biomechanics of individual technique, research should not merely focus on the best performance of an athlete, but it should attempt to analyse the individuals "typical" mode of performance. Namely, it should capture the core biomechanical strategy that governs movement, regardless of the variations that emerge in repeating the same action"*

Within-participant study design is becoming more acceptable as it allows coaches and researchers the ability to understand how an athlete acquires a movement technique (Barris, 2013; Bartlett et al., 2007; Farana, Irwin, Jandacka, Uchytil, & Mullineaux, 2015; Gervais & Dunn, 2003; Gittoes et al., 2011; Hiley et al., 2013; Komar et al., 2015; Newell & Slifkin, 1998; Schöllhorn & Hans, 1998; Wilson et al., 2008). The basic rationale for a within-participant study design is that individuals are unique, with no two individuals being alike (Bates, 1996). Group study designs limit sports scientists' ability to observe an individual's coordination signature as it normalises group participant data; thus, consequently, concealing important participant specific information (Bartlett et al., 2007). Bates (1996) identified that humans cannot replicate a movement pattern exactly the same way due to the various physical and environmental constraints imposed during the performance of a skill. To adequately understand an individual's technique when performing a skill, the number of trials collected per movement pattern should be increased (Bates, 1996; Mullineaux et al., 2001). Increasing the number of repeated measures provides a more holistic evaluation of an individual's motor behaviour (Dona et al., 2009) and it provides a more reliable measure of the movement pattern.

Statistical variability

Statistical variability refers to measures of centrality around a mean (Harbourne & Stergiou, 2009). The two most common statistical representations of variability are the descriptive measures of standard deviation and the coefficient of variation. Standard deviation is calculated as the root mean square of the differences from the mean (Vincent, 1999) and is termed as the absolute measure of variability (Bartlett & Robins, 2008, p. 291). Standard deviation is a useful measure as many statistical techniques are based on the comparison of the mean as the central tendency of the data, with the standard deviation representing the dispersion of the data. Within-Participant coefficient of variation is the standard deviation expressed as a percentage of the mean and is an important measure of the reliability of performance when the standard deviation comes from repeated measures of a single subject (Hopkins, 2000a). Coefficient of variation represents an individual's sports performance variability from trial to trial (Hopkins, 2000b) and is termed as the relative measure of variability (Bartlett & Robins, 2008, p. 291).

Both measures of statistical variability are valuable for sports scientists and coaches when assessing an individual's performance variability from repeated measures of the same movement pattern (Hopkins, 2000b). However, a limiting factor of these descriptive measures is that they are derived from time or magnitude specific data (discrete measures) and may miss important information during a continuous movement pattern (Dona et al., 2009; Harbourne & Stergiou, 2009; Ryan et al., 2006). Traditionally the optimal models of performance have encouraged biomechanists to search for discrete performance parameters that contribute the most to a successful outcome (Glazier et al., 2006). The classical discrete measures technique draws conclusions from the time or magnitude specific measures, thus sacrificing the full data sequence (Ryan et al., 2006). Multiple movement signals could represent the same mean and standard deviation, however the structure of the signal to create these could be very different

(Newell & Slifkin, 1998). In order to provide information on the coordination patterns that help facilitate these measures, variability within an entire movement cycle has previously been graphed as standard deviation curves (Bardy & Laurent, 1998; Farana et al., 2015; Hamill et al., 1999). The standard deviation curve technique provides a qualitative understanding of the time-evolutionary characteristics (Newell & Slifkin, 1998) and fluctuations within repeated measures of the same movement pattern. However, this technique still lacks the quantitative statistical analysis. To quantitatively analyse the variability within an entire movement sequence, the emerging statistical technique of functional data analysis (FDA) has become available to sports biomechanists.

FDA was originally introduced by Ramsay and Dalzell (1991) as a holistic approach that considers the entire movement cycle as one entity rather than a set of individual numbers. FDA provides a "toolkit" to analyse groups of curves (functional data). Functional principal components analysis (*f*PCA) is a technique within the FDA "toolkit", where principal components are produced and are represented as functions. Currently, *f*PCA has been used to biomechanically analyse the variability within continuous time-series data from multiple sporting contexts including; rowing (Warmenhoven et al., 2015), swimming (Sacilotto, Warmenhoven, Mason, Ball, & Clothier, 2015), weight lifting (Kipp & Harris, 2015; Kipp, Redden, Sabick, & Harris, 2012), as well as gait kinematics (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Dona et al., 2009; Donoghue, Harrision, Coffey, & Hayes, 2008; Ryan et al., 2006).

*f*PCA transforms the original set of data into a small set of linear combinations that demonstrate the trends of variability and quantifies the difference from the mean for multiple time-series trials (Dona et al., 2009; Donoghue et al., 2008; Ryan et al., 2006). These linear combinations are known as principal components, with the first principal component representing the largest amount of variation within the movement pattern. Generally, the principal components representing ≥95% of the total variance within the movement cycle are taken forward for further explanation. Biomechanical interpretation of the variability represented by each principal component is displayed by plotting the mean movement sequence curve with two additional curves created by adding and subtracting a multiple of the principal component (Ramsay & Silverman, 2002, p. 24). The positive (+) and negative (-) curves indicate the high and low scorers for each particular *f*PC extracted. The scalar mean of the multiple performance trials that contribute to each *f*PC are referred to as the *f*PC scores (Warmenhoven et al., 2015; Dona et al., 2009; Ryan et al., 2006). These scores have been used to differentiate the type and amount of variability for individual participants. Scatterplot analysis has been used to represent specific characteristics of a participant (Ryan et al., 2006) and to determine whether there are any kinematic differences between skill levels (Dona et al., 2009; Sacilotto et al., 2015; Warmenhoven et al., 2015). The emerging statistical technique allows sports biomechanists to move from the traditional discrete measures analysis to the analysis of entire movement patterns, and thus more appropriately understanding how a skill is achieved (Glazier et al., 2006).

It must be noted that variability can come from both biological and technological components which consist of 1) characteristics of instrumentation used to collect and process data, 2) marker accuracy and skin movement and 3) within-participant variability (Rodano & Squadrone, 2002). The biggest concern when assessing variability of repeated measures is the level of technological error that has contributed to the final outcome. It has, however, been concluded that a major source of variability can be attributed to biological variability of human movement (Rodano & Squadrone, 2002). To prevent technological error, anatomical landmarks should be made clear, automatic digitisation should be used to provide the best accuracy during video analysis (Bartlett et al., 2006) and the relative motion of skin artefacts needs to be considered when using anatomical locators such as markers and sensor units (Forner-Cordero et al., 2008).

Implications: Variability

The practical application of understanding the principles of within-participant variability is important when analysing springboard diving. Springboard diving is an individual sport where athletes receive scores from the judges rating their performance. Within Australia, there are a limited number of athletes who are able to perform an international standard dive list (Barris, 2013). In order to improve the top elite athletes' performance and increase the capabilities of sub-elite athletes, individual performance analysis can benefit diving associations. During competition, divers must overcome the physical, environmental and task specific constraints (FINA diving rules, Appendix 1) that are imposed on them to achieve a high scoring dive. The succeeding section of this review will specifically focus on the existing biomechanical research incorporating the three categories of constraints.

Biomechanics of the forward dive category from the 3m springboard

The execution of a dive is influenced by criteria from FINA that is provided to athletes, coaches and judges. For example a diver's takeoff needs to be "bold, high and confident". The dive flight must be at "all times aesthetically pleasing" and "the entry into the water should in all cases be vertical, not twisted, with the body straight, the feet together, and the toes pointed" (FINA, 2014), Appendix 1). A judge's final impression of the dive is the entry, where judges are looking for a "ripped entry" (minimal to no splash), which is commonly known to result in a higher score from the judges (Brown, Abraham, & Bertin, 1984; Driscoll, Gaviria, & Goodwill, 2014; Qian, Zhang, & Jin, 2010).

The springboard: an environmental constraint

The current FINA regulated springboard is the "Maxiflex B springboard" (Duraflex International Corporation, Sparks, NV, USA). The Maxiflex B is constructed with a single-piece extrusion of aluminium alloy and is 4.877m in length (Figure 2), with the most compliant aspect being the last 0.70m (Sprigings, Stiling, & Watson, 1989). The board is fixed to a base via a hinge and supported by an adjustable fulcrum, centrally located 1.88m from the fixed end. Hooke's law of elasticity applies to the springboard, as it can be represented as a linear spring (Sprigings et al., 1989; Sprigings, Stilling, Watson, & Dorotich, 1990). The law states that the extension of a spring is directly proportion to the load added, as long as the load does not exceed the elastic limit.

The springboard can be considered to be an environmental constraint, as divers must overcome the properties of the springboard in order to gain the benefit of the compliant surface. Divers are constrained by the stiffness of the springboard, which is the resistance of an object to deform (Leckie & Bello, 2009, p. 48). The stiffness of the springboard can be manipulated by changing the fulcrum setting (from a scale of 1-9) and by applying force (Jones & Miller, 1996; Miller & Jones, 1999; Sprigings et al., 1989; Sprigings et al., 1990), with greater force and a looser fulcrum setting resulting in greater downward deflection. As the deflection of the springboard is increased the amount of elastic strain energy stored in the spring system increased (Jones & Miller, 1996).

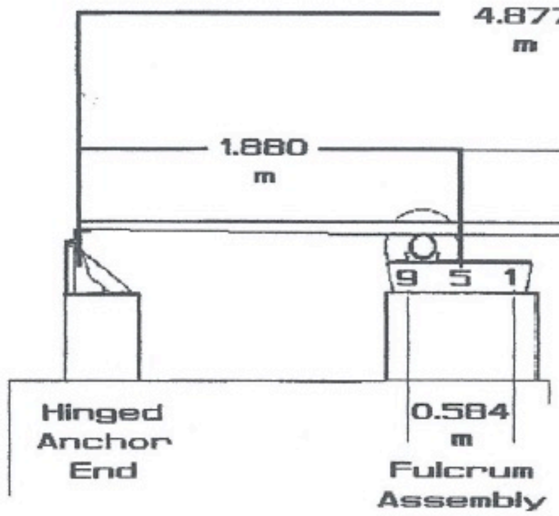

Figure 2. Schematic representation of the springboard (Miller, Osborne, & Jones, 1998)

A second constraint relating to the springboard is the range of oscillation cycles the springboard goes through during the running approach (Miller et al., 1998). A diver will perform a hurdle during their approach (high hop from one leg) to travel forward to the tip of the springboard (Miller, Zecevic, & Taylor, 2002; Sanders & Wilson, 1988). During the hurdle flight the springboard moves through 2.25 to 2.5 oscillation cycles (Jones & Miller, 1996). The oscillation cycles are influenced by the proportion of the board that overhangs the fulcrum, the effective mass (Sprigings et al., 1989), with a larger portion resulting in longer durations of oscillation cycles. A diver's interaction with the springboard's oscillation cycle is important, as it will influence their ability to generate and store energy into the spring system. Theoretically, there is a benefit of increasing the elastic strain energy from a looser fulcrum setting. This, however, depends upon the organismic constraints of a diver; whether or not they have jumping ability and strength (leg and hip) to manipulate a more compliant springboard (Jones & Miller, 1996).

The forward dive category: The task constraint

A forward dive may be executed in three different positions; tuck, pike and straight (Figure 3), with two most commonly performed forward dive category positions being the tuck and piked. The tuck position is achieved by folding the body into a tight ball with the hands grasping the shins and the pike position is achieved by folding the body at the hips onto straight legs (Koschorreck & Mombaur, 2011). Both the tuck and pike dive positions require a diver to extend out into a straight position before entering the water. During the straight position the hips and knees are extended, while the shoulders are flexed.

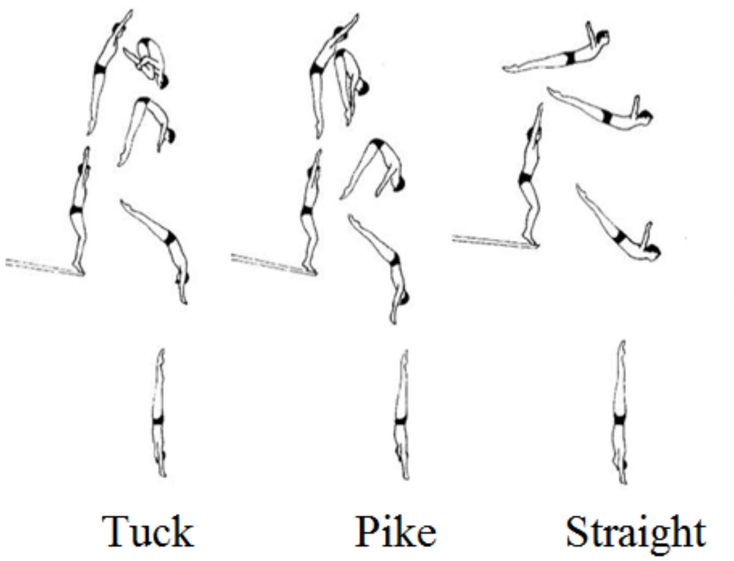

Figure 3 Dive flight positions taken from (FINA, 2014)

Running Approach

A running approach is used for all dives performed from the forward category. This approach is used rather than a standing jump as it increases the amount of energy that can be stored in to the springboard and subsequently returned to the diver. There are two classes of running approaches; the traditional and the hurdle pre-flight approach (Miller et al., 1998; Miller et al., 2002) (Figure 4). During the traditional approach a diver takes at least three fast steps followed by a push off one foot, which is commonly known as the hurdle. A diver choosing to use the pre-flight approach will either leap off one foot or jump from two feet during their last step. Both approaches must meet the task constraint of initiating the hurdle from one leg hurdle as shown by the hurdle stance in Figure 4.

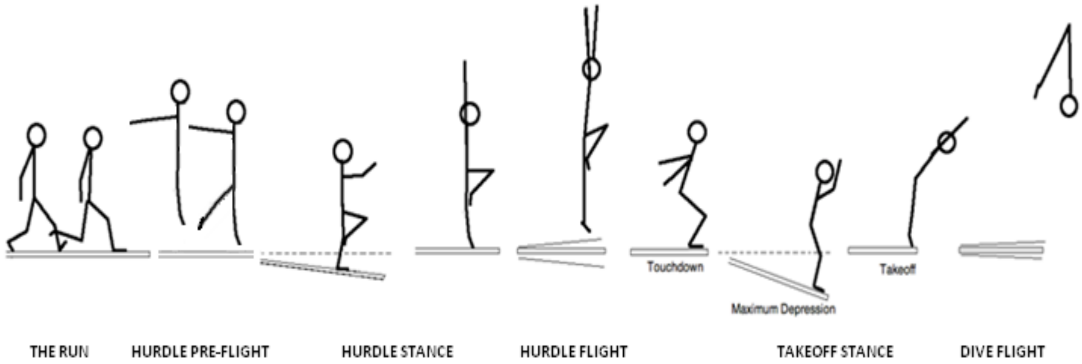

Figure 4. Hurdle pre-flight running approach; modified from Walker (2010)

The hurdle is one of the most important features of the dive approach as it allows the diver to travel forward to the tip, reaching the most compliant portion and influence the amount of kinetic energy that is transferred into the spring system. A diver must coordinate their hurdle flight with the springboard oscillation cycles to allow them to catch the springboard at its optimum position of maximum downward vertical velocity (Boda, 1992; Jones & Miller, 1996; Miller et al., 1998; Sprigings et al., 1989; Sprigings et al., 1990). Once the diver has touchdown with the springboard they will apply a downward force to maximally depress the springboard placing as much energy into the spring system as possible. Following maximum depression the diver rides the springboard as it is recoiled, allowing them to be projected into the dive flight (Miller et al., 1998)

Dive flight energy generation

Mechanically, energy is the capacity to do work (Hamill & Knutzen, 2003, p. 362). A diver must generate energy to develop the linear and angular momentum required to complete the task demands of gaining sufficient height, distance and rotation from the diving surface at takeoff (Hamill, Golden, & Williams, 1985; Hamill, Ricard, & Golden, 1986; Miller, 2000). Proceeding the hurdle flight, the potential and kinetic energy of a diver will be converted to the springboard as elastic strain energy. The diver will continue to work the spring system by applying a downward force. The linear stress-strain relationship of the springboard results in the springboard returning to its original position after going through the downward deformation (Sprigings et al., 1989). As the springboard recoils the elastic strain energy is returned to the diver to utilise during the dive flight. (Sanders & Wilson, 1988) (Figure 5).

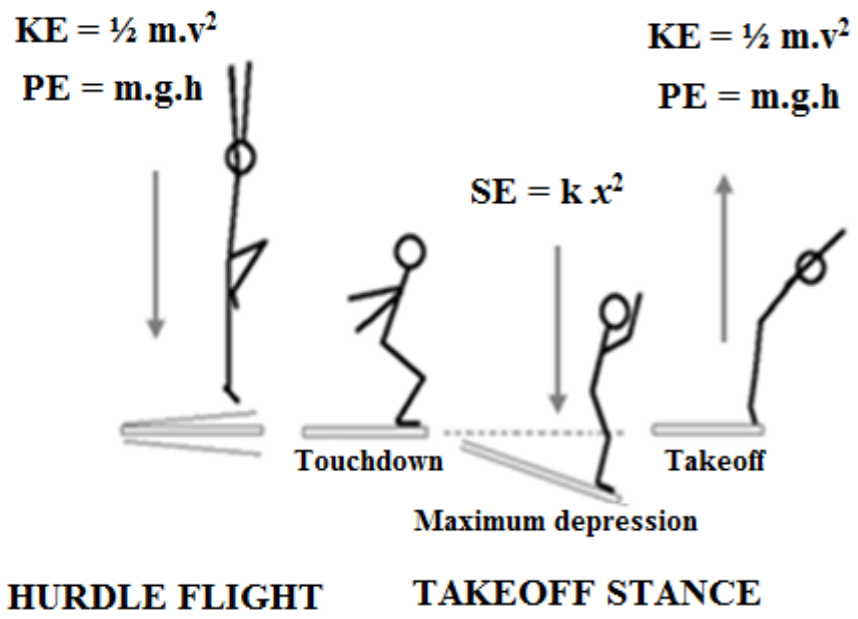

Figure 5. Energy conversion during the hurdle flight touchdown and maximum depression, with the energy return during the recoil of the springboard.
m = mass, v = velocity, g = gravity, h = hurdle height, k = spring constant and x = deformation.

A diver's physiological and musculoskeletal systems must manipulate the constraint imposed on the task at hand (height, distance and rotation), by increasing the downward displacement of the springboard and thus elastic strain energy stored within the spring system. After touching down with the springboard from the hurdle flight, the ankle, knee and hip joints flex as a mechanism to absorb the impact force of landing (Miller, 1973; Miller & Munro, 1985a). This is where benefits or shortcomings can be realised through the interaction of an individual's organismic constraints with their environment. A diver will either have the physical ability to increase the energy placed in the system or eccentrically absorb any potential energy that may have been returned to them during the springboard recoil. On touchdown, springboard reaction forces act upwards upon a diver, subsequently instigating lower limb flexion torques. To prevent extended eccentric contraction of the quadriceps (increased myofilaments detachment), the lower limb must concentrically produce a powerful extension torque greater than the opposing flexion torques (stretch-shortening cycle) (Jones & Miller, 1996; Sanders & Gibson, 2000; Sanders & Wilson, 1990). A diver with the physical attributes to work the environmental constraint by applying more energy into the spring system, is able to gain more energy return and thus greater peak dive heights (Miller et al., 2002; Sanders & Gibson, 2000; Sayyah, Yeadon, Hiley, & King, 2016; Sinclair et al., 2012).

Dive flight linear and angular momentum

The energy stored and returned from the springboard is used for both the translational and rotational task demands of the dive flight. The rotational demands of a dive will influence the resultant height achieved during the dive flight. As the number of somersaults increases, an increased quantity of strain energy is converted to kinetic energy of rotation and therefore the ratio of energy available for linear translation is reduced during the takeoff (Sanders and Wilson 1988). Newton's second law of angular motion specifies that the rate of change in the body's angular momentum is proportional to the torque acting upon (Hay, 1993). As torque is equal to the product of force and the perpendicular distance from the force applied to the body's centre of gravity, the body posture at takeoff will greatly affect the magnitude of angular momentum (Williams, 1985).

As rotational requirements increase, a diver must create a larger moment arm (forward body lean) for the springboard reaction force to develop the greater angular momentum (Sanders & Gibson, 2000; Sanders & Wilson, 1988). When forward lean at takeoff increases, vertical impulse is decreased via a reduction in vertical reaction forces and recoil duration, vertical velocity at takeoff decreases and horizontal velocity at takeoff increases; with these factors consequently leading to a decrease in the vertical displacement from the springboard (Golden, 1981; Miller, 1984; Miller & Munro, 1984; Miller & Sprigings, 2001; Sanders & Wilson, 1988).

Angular momentum is the quantity of angular motion of an object and is the product of angular velocity and mass moment of inertia (Hay, 1993). The law of conservation of momentum states that angular momentum will remain constant when there is no external torques acting. Therefore, once in the air, divers are only able to manipulate their rotational mechanics by increasing or decreasing their mass moment of inertia (Miller & Sprigings, 2001; Sanders & Gibson, 2000). The amount of rotation achieved during a somersault is termed the change in angular displacement. Generating sufficient linear and angular momentum are important to achieve the angular displacement required to perform additional somersault revolutions. Previous investigations analysing the kinematic differences of male and female divers have highlighted that males were able to perform 3½ pike somersault dives at a greater success rate when compared to female divers, by generating greater angular momentum at takeoff and linear translation (flight time) (Miller & Sprigings, 2001; Sanders & Gibson, 2000). The increased angular and linear momentum allowed the male athletes to spend a longer duration of time in the somersault position and therefore achieve to required angular displacement.

Dive flight phases

Dive flight has previously been identified by four key events; initiation of somersault, maximum flexion, initiation of extension from somersault and entry preparation (Naundorf, Wenzel, & Krug, 2008; Sanders & Gibson, 2000; Schuler, Schleichardt, Kothe, & Witt, 2012), (Figure 6). Divers must link the phases of flight in order to meet the task constraint of a vertical body alignment on water entry (FINA, 2014) and prevent being penalised from the judges due to misalignment of the body. Entering the water in a non-vertical position can be a result of not generating the required angular momentum at takeoff or not having the required time to prepare for entry into the water (Sanders & Gibson, 2000).

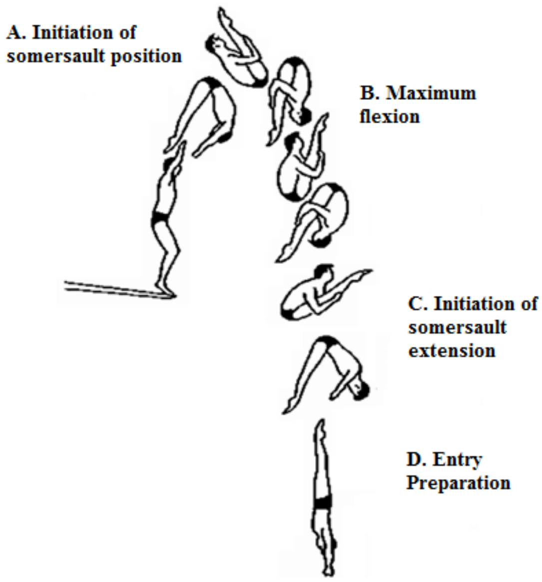

Figure 6. Four key events of the dive flight, edited from FINA (2014).

Water entry

The entry is the final element the judges score before a diver is fully submerged into the water. This final task component of a dive should be vertical, not twisted, with a straight body alignment, feet together and toes pointed (FINA, 2014). Similar to a gymnasts dismount from an apparatus (Gervais & Dunn, 2003), the entry is the final impression of the dive performance that can be retained by the judges. A ripped entry (minimal to no splash) is an ideal performance outcome, with larger splash height and width resulting in fewer marks from the judges (Driscoll et al., 2014; Miller & Zecevic, 2005; Qian et al., 2010)

Springboard diving methodological procedures

Research presented in this review have all collected data via two-dimensional video footage, which requires digitisation to analyse the kinematics of a diver. Two common issues can arise when using video digitisation: (1) low camera resolution and shutter speed making the exact anatomical landmarks difficult to identify and (2) the arduous nature of digitising which typically restricts the kinematic analysis to a single performance trial per participant (Glazier et al., 2006; Helten, Brock, Müller, & Seidel, 2011).

Previous methodological procedures have largely been conducted during competition events that restrict researchers to the number of trials they are able to collect. This data has provided the typical kinematic requirements to perform different dives, with a particular focus on the dive approach. The typical kinematic requirements have provided sporting institutes with the ability to combine the readily available biomechanical data to help build and mould training programs in order to produce successful athletes. However, the time consuming nature of two-dimensional digitising restricts the ability of researchers to apply the dynamical systems theory approach to understand an individual's motor behaviour, coordination and functional adaptations abilities.

Three-dimensional optical tracking systems are currently the most common procedural method for land based activities and allow researchers the ability to increase the number of trials per participant. Optical tracking systems use active or passive reflective markers with charged couple device (infrared) cameras to capture a subject's movement within an assigned field of view. Once calibrated to a participant, the system automatically recognises anatomical landmarks and integrates this information into a kinematic software package to output the data of interest. However, disadvantages of the optical tracking systems include expense, requirement of high speed processing devices and are constrained to a controlled laboratory based environment (Gouwanda & Senanayake, 2008). When assessing diving, the expense of setting up an optical tracking system dramatically increases, due to water proofing and rigging required to position the cameras over the pool. A second hindrance is the risk of the full body marker sets falling off the diver on water entry after every dive trial. This results in the time consuming procedure of reattaching the reflective markers, at risk of not precisely relocating them to the original position. Both two and three-dimensional video analysis prove to have disadvantages that out way the advantages when collecting data for springboard diving.

New technology – Inertial Measure Units

Recently, inertial measure units (IMUs) have been presented as a feasible data collection tool for sports biomechanists as a means to surmount the expense, time consuming and environmentally constraining nature of video analysis (Gouwanda & Senanayake, 2008). Engineering companies, such as IMeasureU® (Auckland, New Zealand), have developed micro sensors that contain three axial gyroscopes, accelerometers and magnetometers, with the ability to measure the rate of rotation (deg/s), linear acceleration (m/s^2) and magnetic field strength (µT) (Finch, Lintern, Taberner, & Nielsen, 2011).

A majority of the research conducted by biomechanists utilising IMUs has been to assess segmental orientation and displacement as well as joint angles (Bauer et al., 2015; Bergamini et al., 2013; Bergmann, Mayagoitia, & Smith, 2009; Fasel, Spörri, Kröll, Muller, &

Aminian, 2015; Leardini et al., 2014; Myklebust, Gloersen, & Hallen, 2015; Schwameder, Andress, Graf, & Strutzenberger, 2015). Concerns have been raised about the accuracy and reliability of the new technology when collecting such data. Many papers have conducted their own accuracy and reliability studies for their chosen units before conducting scientific human movement studies. These studies have involved comparisons between the chosen IMUs and optical tracking systems, with conclusions of accepting the output data from the new technology (Bauer et al., 2015; Bergmann et al., 2009; Boonstra et al., 2006; Fitzpatrick & Anderson, 2006; Leardini et al., 2014; Mayagoitia, Nene, & Veltink, 2002; Picerno, Viero, Donati, Triossi, & Tancredi, 2015; Schwameder et al., 2015; Wells et al., 2015).

However, some limitations and cautions have been outlined for the emerging sensor technology. These include: (1) drift in sensor orientations and displacement from the integration of signals, (2) segment anatomical frame misalignment, (3) soft tissue artefacts, and (4) inaccuracies in the underlying biomechanical model for posture estimation (Fasel et al., 2015; Gouwanda & Senanayake, 2008). The drift error when calculating orientation has been reduced with the integration of the three components of the modern IMU; accelerometer, gyroscope and magnetometer (Finch et al., 2011; Gouwanda & Senanayake, 2008). Fasel et al. (2015) indicated that short movement periods of less than 30s were not affected by integration drift error and thus, a sport such as springboard diving where the skill is performed within 1.6s (Sanders & Gibson, 2000) should not be impacted by this limitation. The anatomical frame misalignment and soft tissue artefacts can be minimised by correctly aligning the IMU to the anatomical planes of motion and by firmly securing the units to the skin to prevent any relative motion with respect to the skin artefacts (Forner-Cordero et al., 2008).

Theoretically gyroscopes embedded within an IMU can objectively assess the angular velocity, direction of rotation and degree of rotation of a moving object (Brunetti, Moreno, Ruiz, Rocon, & Pons, 2006; Harding, Mackintosh, Hahn, & James, 2008). Angular velocity measures, recorded by embedded gyroscopes, have been compared to optical systems and concluded as reliable (Bergamini et al., 2013; Boonstra et al., 2006; Mayagoitia et al., 2002; Picerno et al., 2015). Angular kinematics is a key feature of acrobatic sports, with IMUs providing the opportunity for sports biomechanics to analyse the complex and rapid movement of somersaults. IMUs have been used to analyse entire movement sequences repeatedly within the ecological contexts of trampolining (Helten et al., 2011) and snowboard half-pipes (Harding et al., 2008); providing instantaneous identification of aerial maneuverers about the longitudinal and transverse axes. The ability of IMUs to capture sport-specific movements emphasises the capability of this contemporary technology to provide further detail on athlete demands and performance (Chambers, Gabbett, Cole, & Beard, 2015).

Implications: Springboard diving biomechanics

The practical outcomes from the existing biomechanical research identifies the key elements of performing multiple somersault dives from the 3m springboard, with a practical focus of the interaction of the diver and their environment. A springboard diver must have the correct strength and technique to manipulate the springboard in order to develop adequate energy to generate both the translational and rotational demands of multiple somersault dives. There is limited research analysing the total flight of a diver and this may be due to the time consuming nature of two-dimensional video analysis. The more ecologically and practically feasible methodical tool of IMUs provides an opportunity for sports scientist to measure springboard diving in greater depth.

Variability of movement patterns relating to springboard diving

Currently, there is limited existing literature analysing the variability of a springboard diver's approach and flight mechanics. Therefore, the following section of this review aimed to report the findings from these studies as well as from sports with similar movement patterns that can be translated to springboard diving.

Running approach variability

> *"When executing a running dive from the springboard, the run shall be smooth, aesthetically pleasing, and in a forward direction to the end of the springboard with the final step being from one foot"* (FINA, 2014, p. 228)

A diver is judged from the moment they initiate their starting position, with the potential to lose points before they have even completed the aerial proportion of the dive. A re-start can be ruled if a diver baulks (stops) their approach, resulting in an automatic loss of two points from their total score and a failed dive (zero score) can be ruled if a diver falls or jumps from the end of the springboard without completing the elected dive task. The regulation of the approach is important to prevent the loss of marks from the performance score.

Olympic-level springboard divers have previously been shown to reduce their step length variability preceding the hurdle, with a group mean coefficient of variation equalling 18.6% for the first two steps that reduced to 13.6% for the last step (Slobounov, Yukelson, & O'Brien, 1997). The mean variability of the approach steps was also shown to decrease as a function of the dive degree of difficulty. Forward straight jumps produced the highest mean variability (19.6%), followed by forward 1½ tuck somersault dive (18.3%) and finally forward 2½ tuck somersault dive (11.3%). Preparatory movements of the task can be considered as precursors that facilitate the execution of the aerial portion of the performance, where expert divers explore and utilise efficient strategies to sequentially freeze or un-freeze the biomechanical degrees of freedom to accommodate the task demands (Slobounov et al., 1997).

Similar to Slobounov et al. (1997), footfall variability during the long jump approach has been reported to decrease in the final four to five strides from the takeoff board (Lee, Lishman, & James, 1982; Panteli, Theodorou, & Smirniotou, 2011; Scott, Li, & Davids, 1997). The task constraint of a fail jump being ruled if an athlete passes the takeoff board provides the significance of this functional adaptation to produce a more consistent takeoff position prior to the aerial phase of the jump. It has been suggested that the decrease in footfall variability during the long jump approach is a result of target-directed visual regulation (Galloway & Connor, 1999; Panteli et al., 2011; Scott et al., 1997). Interestingly, studies analysing the stride pattern characteristics of visually impaired long jump athletes have shown a similar footfall variability decrease in strides closer to the takeoff board (Theodorou, Emmanouil, et al., 2012; Theodorou, Skordilis, et al., 2012). This informs us that approach pattern is functionally regulated through not only perceptual information, but also via kinaesthesia using both the somatosensory and vestibular systems (Bradshaw & Aisbett, 2010; Panteli et al., 2011; Theodorou, Emmanouil, et al., 2012; Theodorou, Skordilis, et al., 2012).

Task specific training programs, with the aim to limit baulked dive approaches, have been implemented to encourage elite springboard divers to learn to accept and adapt to changes (Barris et al., 2014). After the task specific training program, divers were able to achieve greater consistency and stability with their performance-specific outcome measure of water entry, by increasing step length variability; suggesting that they were able to adapt to changes during the preparatory phase. Conversely to Slobounov et al. (1997) and previous long jump studies, within-participant step length variability during both completed and baulked dives increased as the divers moved closer to the springboard (Barris, Farrow, & Davids, 2012; Barris et al., 2014). Furthermore, after the prescribed training task overall variability increased for all athletes. The divers in Barris and colleagues studies may be demonstrating how functional movement variability can be used to attain greater flexibility to achieve successful task execution. Barris et al. (2012) theorised that divers in Slobounov and colleagues study may have presented greater consistency in the approach of more complex dives due to the fact that they did not report any baulked dives and therefore divers may have only chosen to complete dives with ideal approaches.

Takeoff variability

When performing an aerial manoeuvre, whether it is a simple jump or a complex somersault, the takeoff is the transition from the approach phase to the flight phase (Vaverka, Janura, Elfmark, McPherson, & Salinger, 1996). Gymnasts repeatedly performing a backward somersaulting tumbling pass are subject to some variability as they are required to manipulate their compliant environmental surface as well as adapt to changes within their approach and takeoff (King & Yeadon, 2003). King and Yeadon (2003) developed a simulation model to assess an elite gymnasts ability to adapt to these variables. They reported that gymnasts were able to functionally adapt to perturbations during the approach by altering their joint torques and consequently adjust their muscle activation timings, thus changing their linear and angular momentum at takeoff to produce a successful somersault. Similarly, Gittoes et al. (2011) concluded that localised takeoff control strategies and modulations are used by gymnasts to generate skill specific movement patterns and performance indicators of the flight.

Body alignment on takeoff has previously been shown as the most consistent aspect of the approach for Olympic-leveled springboard divers (Slobounov et al., 1997). Similar to step lengths, takeoff hip angle variability decreased as dive difficulty increased with a mean coefficient of variation of 12% for the forward straight jump, 8% for the forward 1½ tuck somersault dive and 5% for the forward 2½ tuck somersault dive. Consistency in the body alignment on takeoff is important as it defines the quality of the aerial aspect of the dive (O'Brien, 1992, as cited by Slobounov, 1997). With practice, the hip angle variability significantly reduced for the forward straight jump and the 1½ tuck somersault dive was also shown to reduce with practice. Repetition of performance is associated with the ability to functionally regulate movement patterns in order to generate the required dive flight (Slobounov et al., 1997).

Flight phase variability

The flight phases of an aerial manoeuvre will dictate a gymnast's ability to land successfully and safely on the ground. Perturbations during the takeoff can be resolved by functionally changing body posture configurations with respect to the centre of mass during flight to produce a task specific and safe ground landing (Bardy & Laurent, 1998; Gittoes et al., 2011; King & Yeadon, 2003). By functionally changing body postures during flight, a gymnast is able to increase or decrease their mass moment of inertia, manipulating their rotational speeds and thus the amount of rotation achieved in different portions of flight (Bardy & Laurent, 1998; Lee et al., 1992; Requejo, McNitt-Gray, & Flashner, 2004; Yeadon & Hiley, 2014). Highly skilled gymnasts have increased variability during somersault unfolding (opening), with decreased body orientation variation when approaching the ground (Bardy & Laurent, 1998). This compensatory variability acts to functionally regulate angular braking (Lee et al., 1992) in order to adapt to changes during the different phases of the somersault. To land reliably on the ground gymnasts need perceptive (optical) information to regulate their angular braking so that ratio of their body angle to vertical with the rate of change (angular tau dot) increases to reach zero, resulting in an upright landing posture (Lee et al., 1992; Bardy and Warren 1997). Dancers employ similar adaptions with high levels of trunk coordination variability during the decent of a jump to compensate and correct for segmental over rotation during flight (Smith, Siemienski, Popovich, & Kulig, 2011). For both gymnasts and dancers, existing literature suggests that body orientation variability is essential in producing safe landings in an upright position on the ground.

Aerial movements are performed in a limited time frame. For example, gymnasts are able to generate a time of flight of 0.6s for a standing somersault (Bardy & Laurent, 1998), while divers are able to generate a 1.6s time of flight from the 3m springboard when performing a 3½ pike somersault dive (Sanders & Gibson, 2000). To perform these complex movement patterns it has been suggested, in line with the traditional motor learning perspective (Gittoes et al., 2011), that the ability for an expert to produce the same movement outcome is through stability (Bardy & Laurent, 1998). However, Bardy and Laurent (1998) went into greater detail to explain that this does not mean that orientation during a somersault was not under functional control. An entire movement sequence can be stable as a whole but the underlying kinematics to produce the stable outcome can be variable. Thus, the conservation of angular momentum is stable and therefore, to adapt the amount of rotation achieved, the mass moment of inertia is manipulated either by performing a more open somersault position to reduce the rate of rotation or a smaller somersault position to increase the rate of rotation. To date, no literature has been published examining the coordination patterns and variability of dive flight.

Water entry variability

Limited analysis on postural consistency on entry is available to sports scientists and coaches, with Slobounov et al. (1997) being the only authors reporting on this aspect of dive performance. They reported that hip angle on entry was consistent (within 6°) for all dive degrees of difficulties, although the dives performed during the Slobounov et al. (1997) study were not of a challenging difficulty for Olympic level divers. The current trend in the sport is seeing divers push their limits by increasing the number of somersault revolutions during dive flight. The more difficult dives may be associated with a reduction in consistency of the entry posture, but currently this is unknown.

Summary

The dynamical systems theory moves away from the traditional control theory, where normative movement patterns were retained from the optimal performance and variability was seen as negative deviations from these norms. The dynamical systems theory views individuals as their own unique entity, with biomechanics capturing the core biomechanical and motor control strategy (Dona et al., 2009) of a movement technique and the functional adaptation surrounding its core. The ideology of moving away from single trial measures in human movement allows biomechanists to understand an individual's strategy when performing a skill. Variability surrounding this strategy is now seen as a functional means for athletes to adapt and manipulate the specific physical, environmental and task constraints imposed. This is done with the aim to coordinate and control movement phases to produce a successful movement pattern (Bartlett et al., 2007; Newell, 1986).

Existing biomechanical analyses of springboard diving have provided a comprehensive overview of the key elements required to perform highly complex dives. To date, there has been a key focus on the manipulation of the springboard during the approach and takeoff to develop both linear and angular momentum of the dive flight (Golden, 1981; Jones & Miller, 1996; Miller, 1973, 1981, 1984; Miller & Munro, 1985a; Miller et al., 1998; Miller et al., 2002; Sanders & Gibson, 2000; Sanders & Wilson, 1988, 1990; Sprigings, Stilling, & Watson, 1988; Sprigings et al., 1990). The key findings highlight that springboard divers must manipulate their environmental constraint by maximising the extension torques in their lower limbs to: (1) reduce eccentric absorption of kinetic energy, (2) increase the downward depression of the springboard and (3) gain a greater energy return for the dive flight. A second feature of the existing literature is that as dive degree of difficulty increases the takeoff posture leans further forward, subsequently increasing the moment arm for the springboard reaction forces. This results in a greater magnitude of angular momentum and consequently a reduced magnitude of vertical linear momentum (dive height). While, existing research has provided detailed technique analysis of the dive approach and takeoff, there have been no attempts to holistically analyse the dive flight itself.

Springboard diving research is commonly based upon the control theory and traditional study design, where normative values are provided for how a dive is achieved from a group of participants. The series of papers by Slobounov et al. (1997) and Barris (2013) were the first (and only) to move from the traditional study design and analyse repeated within-participant kinematics, with a particular focus on the dive approach. Both series of investigators demonstrated that springboard divers were able to functionally adapt, explore, and control the biomechanical degrees of freedom available to them; producing flexibility during their movement patterns to achieve successful task executions. Proceeding the approach, Slobounov et al. (1997) was the only paper to provide a small functional insight on the takeoff and entry posture. Hip angle was measured at both key events, with a reduction in takeoff hip angle variability as dive degree of difficulty increases and an overall consistency for entry hip angle. Body alignment consistency is important as it defines the quality dive (O'Brien, 1992, as cited by Slobounov, 1997).

Currently, there is a gap in the literature for what control strategies are being utilised between the dive takeoff and water entry. A somersault in gymnastics has been suggested to follow the traditional motor control theory, with stability in the landing outcome of repeated measures (Bardy & Laurent, 1998; Gittoes et al., 2011). However, to produce this stability, postural orientation during the flight follows suit with the dynamical systems theory. Gymnasts functionally adapt their body posture orientation (mass moment of inertia) to resolve perturbations during the takeoff and somersault initiation in order adapt the timing and rate of angular braking, producing the stable landing outcomes.

Further research is required to explore the strategies of springboard divers performing multiple forward somersaulting dives from the 3m springboard, in order to understand how successful performance can be achieved.

References for this chapter are included in the list of references at the end of this thesis

CHAPTER 3

The application of inertial measurement units to springboard diving

The following chapter was formatted for submission to the Journal of Sports Biomechanics and is currently in the second round of revisions (reviewers comments received 14/07/2016)

Author contribution statement

As a co-author on the paper presented within this chapter entitled "*The application of Inertial Measurement Units to springboard diving*", as well as being Primary Supervisor throughout the Doctor of Philosophy candidature of Cherie Walker, I confirm Cherie's contribution to the paper as follows:

- Conception and design of the research
- Data collection
- Analysis of data and interpretation of the findings
- Writing the paper and critically appraising content within the manuscript

Signed: Date: 11/08/16

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Discipline of Exercise and Sport Science

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The application of Inertial Measurement Units to springboard diving

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Abstract

Inertial Measurement Units (IMUs) may offer an ecologically valid, reliable and practical method for biomechanical performance analysis. With such potential in mind, Part 1 of this study examined the accuracy of IMUs gyroscopes with an optical system (Cortex 3.3). A calibration formula standardised the IMUs angular velocity output with the optical system. The percentage differences between the two measures = 0.5% ($p < 0.05$), suggesting IMU efficacy for application. In Part 2, the aim was to examine and understand how dive flight angular velocity time series plots change according to dive degree of difficulty. With IMUs attached to three competitive divers performing forward somersault dives, dive flight kinematics were assessed. Biomechanically, a 4½ tuck somersault dive differed to lower degree of difficulty dives in terms of: (1) a rotational delay immediately after takeoff (to gain greater vertical translation); (2) increased total time of flight; (3) greater muscle effort to resist increased centrifugal forces produced by the increased angular velocity (1090deg/s), and (4) greater eccentric control during deceleration allow a safe and vertical entry into the water. IMU's can be effectively utilised and integrated into contexts such as springboard diving for performance analysis and optimisation purposes.

Key words: kinematics, gyroscope, angular velocity, forward somersaults, acrobatics

Introduction

Springboard diving is an evolving sport, with the degree of difficulty increasing for competition success. However, the biomechanical analysis of the sport remains largely unchanged, predominantly utilising time consuming video analysis procedures (Miller, 1984; Miller & Sprigings, 2001; Sanders & Gibson, 2000; Sinclair et al., 2012). The benefits of video analysis relate to the successful capture of kinematic data, and in the assistance of providing feedback for performance optimisation; however, the main and significant disadvantage is associated with the time required to analyse and interpret such data. The challenge therefore remains to biomechanically examine diving performance(s) that utilises an accurate methodology; that is more practically usable; and that provides more immediate kinematic and performance feedback to support skill optimisation.

The development and application of Inertial Measurement Units (IMUs) to assess biomechanical performance is becoming more common, replacing two-dimensional and three-dimensional optical systems. IMUs are not constrained by environmental barriers such as the need for a motion analysis capture laboratory. They have already been used to examine continuous motion during on water rowing (Smith & Loschner, 2002) and alpine skiing (Brodie, Walmsley, & Page, 2008; Fasel et al., 2015), allowing sports biomechanists to analyse entire movement patterns repeatedly within their ecological contexts.

With a majority of the springboard diving literature being related to how the diver interacts with the springboard (e.g., see Jones and Miller (1996)), there is an opportunity to assess the potential application of IMUs to specifically analyse aspects of the dive, such as flight. To our knowledge two-dimensional digitisation of the dive flight is the only known analysis method (see Sanders and Gibson (2000) as an example). Two-dimension digitisation is extremely time consuming and may require multiple cameras angles to record different dive flight parameters to ascertain satisfactory pixel resolution of anatomical markers. IMUs however could help simultaneously reduce equipment requirements and the time required for data-analysis and in providing an evaluation 'turn-around', with the potential to provide more immediate coach-athlete feedback.

A diver will leave the springboard with a certain amount of angular momentum, determined by diver-springboard interaction, which will be maintained until water entry (Sanders & Wilson, 1987). A common trend in the literature available is to report single values for the total angular momentum about the transverse axis (Hamill et al., 1986; Miller & Munro, 1985b; Miller & Sprigings, 2001; Sanders & Wilson, 1987), mean angular velocity during the somersault position (Miller, 2013; Miller & Sprigings, 2001) and total angular displacement, estimated by simple modelling (Sanders & Gibson, 2000). With the dive flight itself being one of the most important aspects of the dive performance, the ability to examine and describe an individual's flight, provides a holistic approach to analyse a complete dive pattern. Dive flight can be broken down into three phases, with the first being the initiation of the somersault position, the second being the tight somersault position itself and the final phase being the unfolding from the somersault position. Determining where the angular velocity acceleration, stabilisation and deceleration occur could be critical to examining and understanding how to perform more difficult dives. Likewise, determining whether, when and how a diver can control and adjust rotation during different phases of multiple somersault dives is significant for skill acquisition and coaching, as well as performance optimisation.

Based on the needs identified, the aims of the present study were in Part 1: determine the accuracy of gyroscopes within an identified IMU model, and in Part 2: demonstrate the practical application of IMUs to springboard diving by examining individual diver's changes in angular velocity, angular displacement and dive flight durations according to dive degree of difficulty. It was hypothesised that angular velocity measures from the chosen IMUs would be comparable to an optical tracking system. Practically, it was hypothesised the IMUs would identify performance characteristics of increasing forward dive degree of difficulties from the 3m springboard, in particular; that as dive degree of difficulty increased the Somersault phase (when the body is the smallest ball like position) angular velocity and angular displacement would increase, while the initial flight (forming the somersault) and opening (leaving the somersault) phases angular displacement would decrease.

Part 1: IMU Validation

Methods

IMU identification

IMeasureU® (Auckland, New Zealand) have developed a hermetically sealed IMU (termed, WIMOTIONZ), allowing the device to withstand the high pressures of water environments. A single IMU contains a tri-axial accelerometer (ADXL345; Analog Devices, Norwood, MA USA), gyroscope (IDG650 and IXZ650; InvenSense, San Jose, CA, USA) and magnetometer (HMC5843; Honeywell, Morristown, NJ, USA), with a sample frequency of 100Hz. The IMeasureU® IMU dimensions are 22mm x 34mm x 10mm with a mass of 12g; which are to our knowledge smaller in size than other micro sensors used in sport (Finch et al., 2011; Marsland et al., 2012; Myklebust et al., 2015; Zijlstra, Goosen, Verheyen, & Zijlstra, 2008). Divers have been reported to reach 1003deg/s for the 3½ pike somersault dive (Miller & Sprigings, 2001) and approximately 1150deg/s for the 4½ tuck somersault dive (Miller, 2013). IMeasureU® imbedded gyroscopes currently have an output range of ±2000deg/s; satisfying the expected angular velocity output ranges for multiple somersault dives. Given these properties, coupled with comfort and no distraction to performance during initial trialling with divers in the training environment, this IMU sensor was taken forward for validation testing.

IMU and optical system comparison procedure

A simplified rotational assessment was conducted between the imbedded IMeasureU® gyroscopes and a fourteen camera lab-based 3D optical system (Cortex 3.3, Motion Analysis Corporation, Santa Rosa, CA, USA), with a 100Hz sample frequency. Four IMUs were attached to a symmetrical rectangular prism with 10 mm retro-reflective markers, and then attached to an electric drill (Bosch PSR 18 SE, Stuttgart, Germany) (Figure 7). A digital protractor verified parallel alignment of the drill axis with the floor. The supplied ImeasureU® software performed an initial calibration routine prior to data collection, requiring the IMUs to remain stable for 2s in order to zero the gyroscope *x*, *y* and *z* angular velocity vectors. To mimic the angular velocity of increasing dive degree of difficulty, three trials at four increasing speed intervals in both rotational directions (forward and backwards) were conducted (slow: $\bar{X}$ 155 ± 35deg/s, medium: $\bar{X}$ 356 ± 63deg/s, fast: $\bar{X}$ 660 ± 110deg/s and maximum: $\bar{X}$ 1555 ± 41deg/s, Appendix 3).

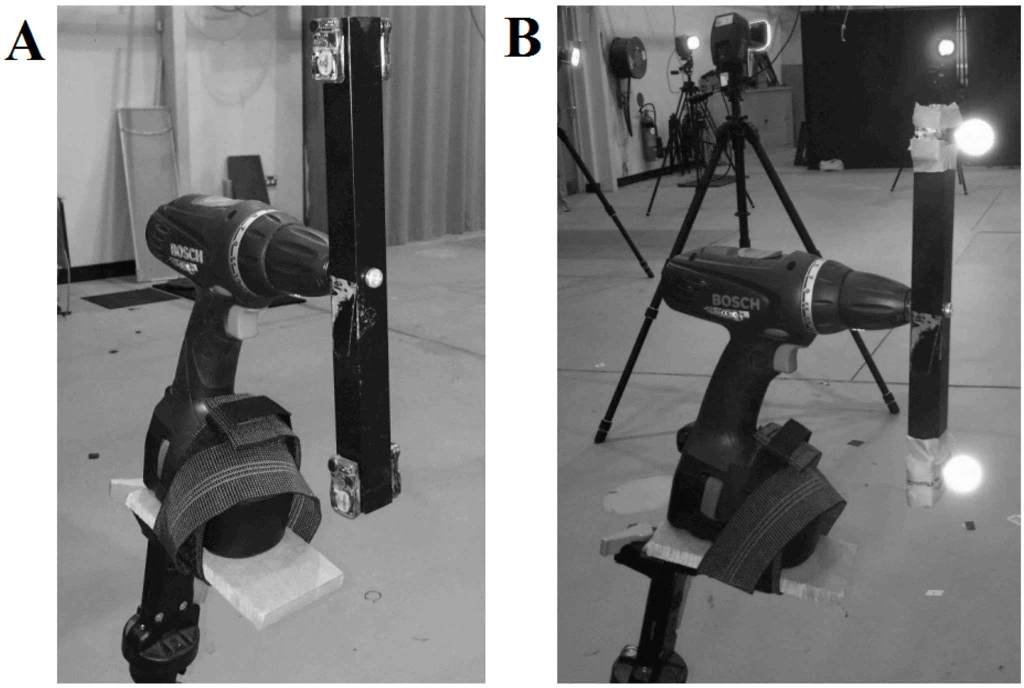

Figure 7. Experimental setup. A – Visual of the four IMU attached to the ends of the symmetrical metal prism. B – Visual of the reflective markers attached to the symmetrical metal prism

IMU calibration and validation data analysis

To standardise the raw IMU angular velocity data with the optical system, a calibration formula was developed. The optical system's data were filtered using a dual pass Butterworth filter, with the analysis of residuals method determining the appropriate cut-off frequency for each speed interval (Winter, 2005) (Appendix 3). Mean angular velocities for both measurement systems were calculated during the stable angular velocity plateau of each speed interval. Initially, Pearson's correlations and linear regressions were conducted between each IMU and the optical system. The individual regression equations were applied to each individual IMUs raw angular velocity data. A secondary linear regression was conducted between the mean IMU angular velocity and optical system, which was applied to the raw angular velocity data of each IMU.

Angular velocity percentage differences, equation (1), at each speed level were calculated between the optical system (ω_{os}) and the four individual IMUs (ω_{imu}) raw data, post application of individual regression equations and post application of the mean regression equation.

$$\text{Percentage difference} \quad = \frac{\omega_{OS} - \omega_{IMU}}{\omega_{IMU}} \omega_{IMU} \times 100 \qquad (1)$$

An independent t-test assessed whether percentage difference significantly decreased when the mean regression equation was applied to the raw IMU angular velocity data. Statistical analysis were all conducted in SPSS (SPSS Statistics for Windows, Version 22.0. Armonk, NY, USA: IBM Corp) with statistical significance set at $p < 0.05$.

To assess the level of drift associated with trapezoidal integration of angular velocity signals, total change in angular displacements were determined for the optical tracking system and individual IMUs post application of the calibration equation. Percentage differences represented amount of drift that occurred when integrating the angular velocity signals.

Results

Individual IMUs all had a Pearson's correlation of $r = 1.000$ ($p < 0.001$) with the optical tracking system. The linear regression between the mean IMUs and optical tracking systems' angular velocity measures also reported a $R^2 = 1.00$. Similar mean percentage differences were found for the application individual IMU regression equations (0.25 ± 0.44%) and mean regression equation (0.47±0.47%) (Appendix 3). Therefore, with an acceptable error difference of only ±0.2% (maximum potential error of 1.6%), the mean regression was chosen as the calibration equation (2) to standardise the IMU angular velocity measures and simplify the analysis process.

$$IMU_{calibrated} = \mathrm{IMU_{raw}} \times 1.012 - 0.0344 \quad (2)$$

The application of the IMU calibration formula, equation (2), significantly reduced the percentage difference for all four of the IMU sensors (Figure 8), with the mean percentage difference reducing from 1.21±0.50% to 0.47±0.47% ($p < 0.05$).

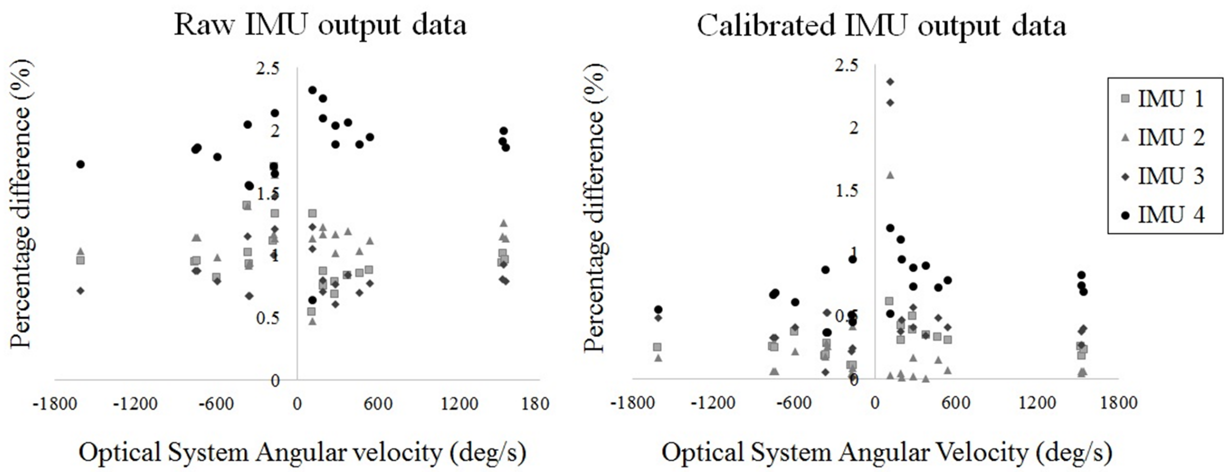

Figure 8. Scatter plot comparison between the raw and calibrated IMU output data.

Figure Notes: Independent samples T-test revealed significant reduction in the percentage difference post the application of the calibration formula for all IMU sensors; sensor 1, 2 and 4 p < 0.001 and sensor 3 p = 0.012.

The drift associated with integrating the IMU angular velocity signals was minimal, with a mean percentage difference of 0.9±0.4% between the optical system and individual IMUs over a mean duration of 6.4±2.5s.

Discussion and Implications

Currently there is limited literature assessing the accuracy of angular velocity measures from IMU gyroscopes. The majority of literature has assessed the accuracy of segmental orientation with respect to the encased accelerometers and gyroscopes (for example, see Zijlstra et al (2008). Our findings for gyroscope angular velocity conforms to normative assessment values of 3D optical systems (<0.5% difference), and is in alignment with prior literature assessing the accuracy of angular velocity with gyroscopes (Bergamini et al., 2013; Boonstra et al., 2006; Mayagoitia et al., 2002; Picerno et al., 2015). Concerns are commonly raised when integrating angular velocity signals to obtain change in angular displacement (Fasel et al., 2015; Gouwanda & Senanayake, 2008). However, prior reports by Fasel et al. (2015) have indicated short movement periods of less than 30s may not be substantially affect by integration drift error. The current IMUs accumulated drift was <1% difference when compared to an optical system over a duration of 6.4 ± 2.5s. A sport such as springboard diving, where a skill is performed within 1.6s (Sanders & Gibson, 2000), should not be greatly impacted by angular displacement errors. The chosen ImeasureU® sensors are not only comfortable and non-distracting to divers due to their size and weight, but also exceed the output signal range required when measuring fast rotating somersaults. With the practicality, positive properties and measurement efficacy identified, we then applied the IMUs for the purposes of Part 2.

Part 2: IMU application in springboard diving

The purpose of Part 2 was to demonstrate practical application of IMUs in springboard diving, by examining individual diver's changes in angular velocity, angular displacement and dive flight durations according to dive degree of difficulty. This was done with a view to understand how skilled performance could be acquired and controlled in more difficult dives.

Methods

Participants

Following institution ethical approval and consent, three elite springboard divers (1 male and 2 female; age = 21.3±4.7years; height = 1.64±0.07m; mass = 60.1±6.2kg) participated. Participant 1 (male) and 2 were internationally ranked elite divers, while Participant 3 was a nationally ranked junior elite diver. All divers were injury free and were in intensive training at the time of data collection, adhering to ten training sessions (25-28 hours) per week.

Procedures and Experimental Set-Up

Data were collected across either three or four of the divers' regular training sessions during a 3-week period. These sessions were in line with the divers regular training and therefore did not interrupt the training routine, i.e. heavy weight sessions were not conducted the morning of the 3m springboard sessions, reducing the potential for muscle fatigue and soreness. Following a standard dry land warm up, two IMUs were adhered bilaterally to the posterior superior iliac spine (PSIS) with adhesive double sided tape and secured with an adhesive film (OpSite^{TM} Flexigrid), to minimise relative motion of the IMU with respect to the PSIS skin artefacts (Forner-Cordero et al., 2008). Two IMUs were applied as precaution in case one became dislodged during training. Neither became dislodged and the signal outputs were in agreement (r = 1.000).

Prior to each session, a high-speed Casio Exilim EX-FH100 camera was placed level and perpendicular to a 3m springboard. The camera was set to a 120Hz frame rate, and a shutter speed of 1/250s. The divers (with coaches present) were instructed to perform their regular aquatic training routine. Each dive performance was video recorded. Before commencing a dive, participants were instructed to stand stably on the springboard for 2-3s, followed by a tap to the IMUs prior to initiating a dive approach. The tap created a clear spike in the gyroscope data and was visible on the video footage, allowing synchronisation between IMUs and video footage.

For the purposes of this study, the single dive category of forward somersault dives was examined. Participant 1 performed three dives of different degrees of difficulties, with his highest degree of difficulty dive (4½ tuck somersaults) currently being the hardest dive performed by male divers internationally. Participants 2 and 3 performed two dives of different degrees of difficulties, with their highest dive (3½ pike somersaults) currently being the hardest dive performed by females internationally. The forward dives performed and number of trials recorded per participant are summarised in Table 1.

Table 1. Individual dive list during recorded aquatic training sessions.

Participant	Dive	n
1	1½ somersaults pike (103B)	5
	3½ somersaults pike (107B)	8
	4½ somersaults tuck (109C)	6
2	1½ somersaults pike (103B)	8
	3½ somersaults pike (107B)	10
3	1½ somersaults pike (103B)	11
	3½ somersaults pike (107B)	13

Table Notes: n is the number of recorded and analysed dive attempts per dive degree of difficulty

Data Analysis

A custom made Matlab script (The MathWorks, Inc., Natick, MA, USA) extracted the output data from each dive, and were then examined in Excel (Microsoft Corp, Redmond, Washington, USA). The calibration formula, equation (2) was applied to the angular velocity data about the transverse (somersault) axis. Time zero was set as the takeoff from the springboard for each trial. A majority of the takeoff events were identified via the synchronisation between the IMUs and video footage. In some cases, where a tap to the IMU was not performed (i.e., the diver forgot), the angular velocity time series plots were visually overlayed to match the takeoff event. Pilot testing with trials that did contain the synchronisation signal revealed that the visual alignment process had a maximum error of 0.02s, with a mean of 0.01s in takeoff event identification.

The dive flight was broken down into three phases, notably Initial Flight, Somersault and Opening (see Table 2). The events signifying the beginning and ending of these phases were identified using video footage, with pilot testing revealing that such events could be identified with accuracy within 0.01s. Timing of each phase was synchronised with the IMU angular velocity time series data. The duration of flight phases and total dive flight were also calculated. Mean angular velocity of the Somersault phase was calculated to determine the rotational speed of each dive. Trapezoidal integration of angular velocity was used to calculate the total change in angular displacement (the amount of rotation achieved) in individual dives, as well as the amount of angular displacement achieved in each of the three flight phases.

Statistical Analyses

Descriptive statistics (mean ± *SD*) were calculated for each kinematic variable (as described above) during each phase of dive flight and according to each dive degree of difficulty. To assess changes in the nine kinematic (dependant) variables according to dive degree of difficulty, multiple one-way ANOVAs with repeated measures were conducted using each diver's individual data set. Due to the risk of Type I errors, Bonferroni adjustments were applied. Pairwise comparisons were used to isolate the location of differences between Participant 1's dives in the three varying degree of difficulty types. Statistical analyses were performed in SPSS, with statistical significance set at $p < 0.05$. Cohen's d was calculated to represent the effect size of the findings and were interpreted as small, moderate, large, very large and extremely large for a d of 0.2, 0.6, 1.2, 2.0 and 4.0 (Hopkins 2010).

Table 2. Definition of the movement phases and the kinematic variables calculated during these phases.

Dive flight phase Kinematics variables	**Definition of the phase**
Total flight Displacement (deg) and duration (s)	Defined from final frame of foot contact with the springboard (takeoff) to the first frame where hands broke the water on entry (Sanders and Gibson 2000).
Initial flight Displacement (deg) and duration (s)	Defined from takeoff to the first frame where the diver's hands touched their legs to form the somersault position.
Somersault Angular velocity (deg/s), Displacement (deg), duration (s)	Defined from the somersault position to the first frame where the diver's hands left their legs.
Opening Displacement (deg) and duration (s)	Defined from the somersault open to the first frame where the diver's hands break the water.

Results

Angular velocity time series plots

IMU gyroscopes provided clear angular velocity time-series plots for all divers. IMU synchronisation with video footage allowed each key event within rotational plots to be interpreted. An example is shown in Figure 9. Here the participant begins their dive by performing 3-4 steps followed by a hurdle. As they touchdown with the springboard from hurdle flight (A, Figure 9), they begin flight preparation by generating as much energy into the springboard during maximum depression (A-B, Figure 9). The diver actively extends his hips at this point, accounting for the negative angular velocity. The diver then begins to flex his hips (B-C, Figure 9) creating the moment arm required to develop adequate torque for angular momentum generation (Sanders & Wilson, 1987) at takeoff (C, Figure 9). A tight pike position is then formed, reducing the divers' mass moment of inertia, and increasing angular velocity about the transverse axis (D-E, Figure 9). Angular velocity deceleration then occurs due to extension of the somersault position (E-F, Figure 9). The diver's hips are extending along with shoulder abduction, resulting in an increase in the mass moment of inertia and a decrease in angular velocity. Interestingly, for this particular dive there is an increase in angular velocity from F-G, possibly due to the shoulders adducting after initial abduction, resulting in a reduction in the mass moment of inertia, in preparation of the straight arm line for water entry. Once arms are aligned with the torso, the diver begins to flex their shoulders with continual hip extension, resulting in final deceleration (G-H, Figure 9).

Intra-Participant Analysis

An example of an IMU angular velocity time-series plot according to increasing degree of difficulty is presented in Figure 10 for Participant 1. Calculated dive flight kinematics for the *Initial Flight*, *Somersault*, *Opening* and *Total Flight* are presented in

Table 3, illustrating the effect of increasing forward degree of dive difficulty. These are summarised according to flight phase:

Initial Flight Phase: For all participants, there was a significant increase in angular displacement during initial flight when performing the 3½ pike somersaults relative to the 1½ pike somersault ($p < 0.001$, $d > 2.5$). Initial flight duration also decreased for all participants from the 1½ to the 3½ pike ($p < 0.001$, $d > 2.3$). Participant 1 was the only diver capable of performing 4½ tuck somersault dive. When increasing the dive degree of difficulty from the 3½ pike to 4½ tuck somersaults, Initial Flight angular displacement significantly decreased (p

= 0.004, d = 2.1), while the duration of this phase showed no significant change (p = 0.098, d =3.0).

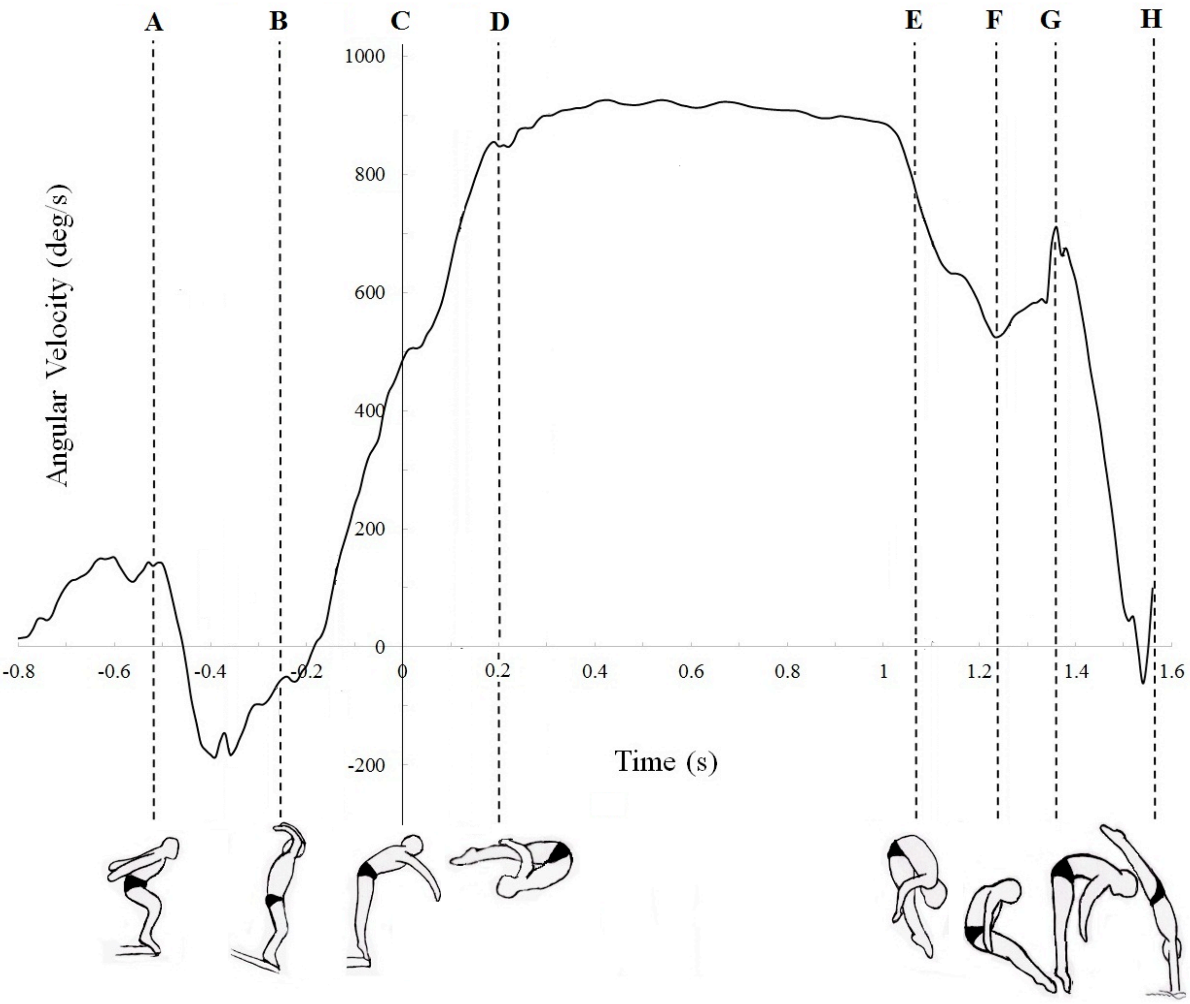

Figure 9. Angular velocity time series plot, example of the 3½ pike somersaults taken from participant 1.

Figure notes: A = Touchdown, B = Maximum depression, C = Takeoff (zero time point), D = Somersault position, E = Somersault open, F = Abduction of shoulder, G = Adduction and flexion of shoulders, H = Hand entry.

Somersault Flight Phase: At this stage, all participants showed a significant increase in angular velocity, angular displacement and duration as the number of somersault revolutions performed increased (i.e., degree of difficulty, p <0.001, d > 6.0).

Opening Flight Phase: At the opening phase, significant decreases in duration and angular displacement across all participants were apparent, as the dive degree of difficulty increased from the 1½ to 3½ pike (all participants) and from the 3½ pike to 4½ tuck (Participant 1), ($p \leq 0.001$, $d > 3.5$).

Total Flight: As expected the angular displacement increased as the dive degree of difficulty increased for all participants ($p < 0.001$, $d > 38.0$). Participants' total flight duration decreased from the 1½ to 3½ pike somersaults ($p < 0.001$, $d > 1.8$). However, Participant 1's total flight duration increased from the 3½ pike to 4½ tuck somersaults ($p = 0.008$, $d = 2.5$).

Discussion and Implications

The purpose of Part 2 was to demonstrate the practical application of IMUs in springboard diving by examining changes in angular velocity, angular displacement and dive flight durations according to dive degree of difficulty. This was done with a view to better understand how skill and control in performing more difficult dives can be acquired. In conjunction with video footage, IMUs provided valuable insight on the performance requirements involved in increasingly difficult dives. Initial Flight is an important phase that transmits the linear and angular momentum developed during the dive approach to the flight itself. When performing the more difficult 3½ pike somersault dive, the participants spent a reduced time (0.05-0.07s) in the Initial Flight phase, but contradictory to our hypothesis, achieved more angular displacement than in their 1½ pike somersaults. During Initial Flight, angular momentum (the product of angular velocity and mass moment of inertia) has been shown to double from the 1½ to 3½ pike somersaults (Miller & Sprigings, 2001) resulting in increased angular velocity. This can also be seen visibly by the increased gradient of the slope in Figure 4. To achieve the 3½ pike somersault dive, divers need to get into the pike position at a quicker rate, reducing their mass moment of inertia and transitioning greater rotational speeds to the next phase of flight (i.e., the somersault phase).

The 4½ tuck somersault dive is a relatively new dive, which was first performed at the Olympics in 2012, thus limited data is available on how elite divers achieve this difficult dive. In understanding how elite divers perform this dive, Participant 1's 4½ somersault tuck dive attempts were compared to his own 3½ pike somersault dive attempts. The 4½ tuck somersault dive had no significant changes in Initial Flight duration, however there was 29° less angular displacement at this phase. When performing a dive in the tuck position, divers have been shown to maintain a more upright posture on takeoff when compared to dives in the pike position. This results in greater kinetic energy from the springboard recoil prior to takeoff, being converted to vertical velocity for the dive flight (Miller, 2013; Miller & Sprigings, 2001; Sanders & Wilson, 1988; Walker, Sinclair, Cobley, Sanders, & Graham, 2014). In Participant 1's angular velocity times series plot (Figure 4), the 4½ tuck somersault dive also illustrated a slight angular deceleration immediately after takeoff. This may relate to Participant 1 being more upright on takeoff, increasing his vertical velocity to gain increased linear translation, and causing a rotational pause. The deceleration occurred for 0.03-0.04s and results in a mean angular displacement loss of 30°, illustrating why there is a significant decrease in angular displacement when compared to the 3½ pike somersault dive. Following Initial Flight deceleration, the gradient of the angular velocity time series slope increased due to the quick formation of a tight tuck somersault position.

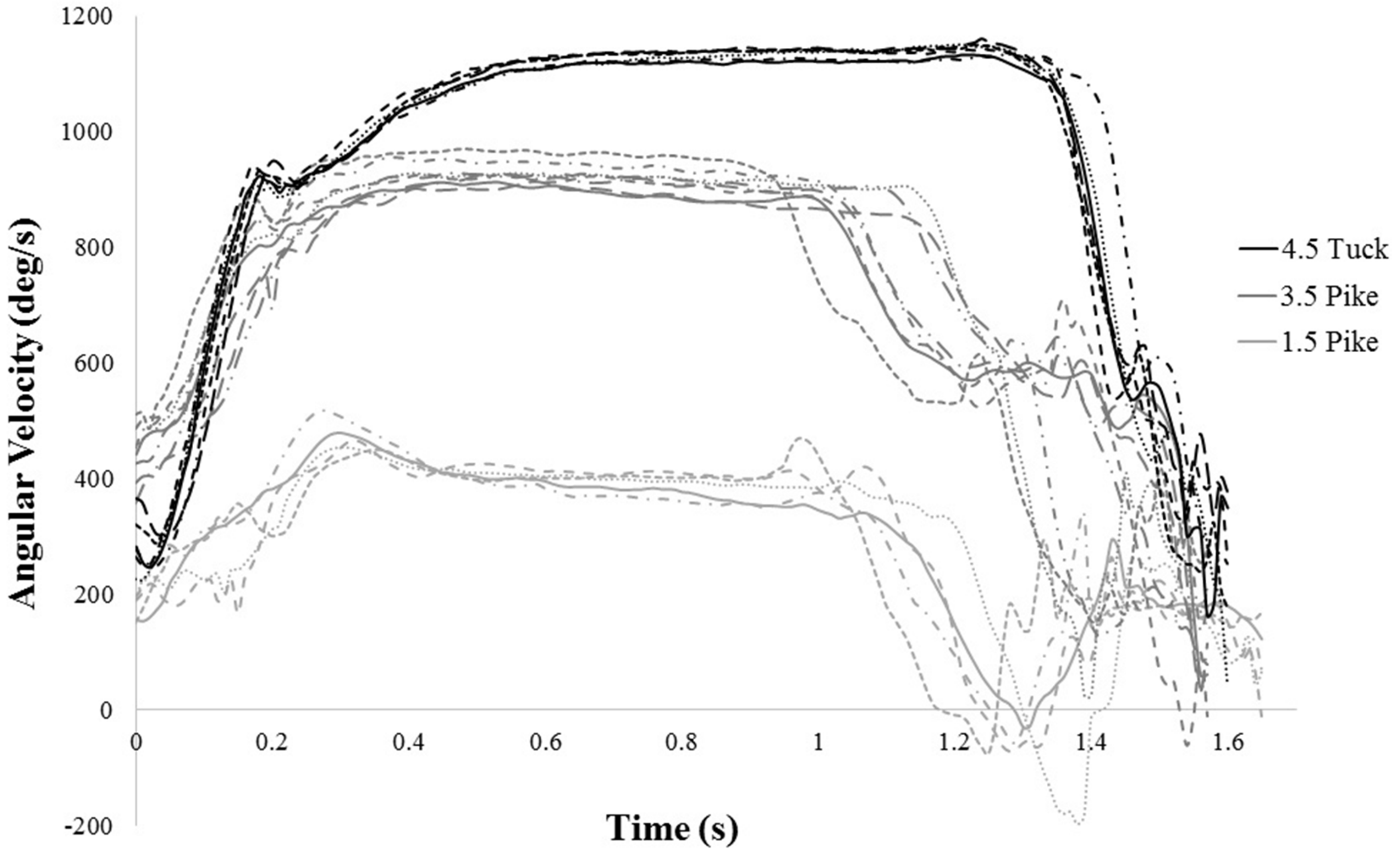

Figure 10. Participant 1's angular velocity time series plots for each dive performance. All dive performances are synchronised by takeoff, 0.00s.

Table 3. Dive flight phases; angular velocity (deg/s), displacement (deg) and duration (s) for each individual participant.

Dive flight phase	Variable	Participant 1			Participant 2		Participant 3	
		1½ pike	3½ pike	4½ tuck	1½ pike	3½ pike	1½ pike	3½ pike
Initial flight	Angular displacement (deg)	84.3 ± 13.3	123.6 ± 15.0	95.0 ± 11.9*	93.6 ± 9.4	171.0 ± 9.1	91.2 ± 13.2	148.0 ± 15.5
	Duration (s)	0.27 ± 0.03	0.20 ± 0.01	0.17 ± 0.01*	0.29 ± 0.01	0.24 ± 0.01	0.26 ± 0.03	0.20 ± 0.02
Somersault	Angular velocity (deg/s)	451.2 ± 18.9	904.5 ± 22.3	1090.3 ± 6.9	500 ± 12.3	865.7 ± 10.7	468.1 ± 43.5	885.4 ± 7.1
	Angular displacement (deg)	51.6 ± 12.1	822.2 ± 53.8	1304.0 ±17.9	62.6 ± 11.9	806.5 ± 15.6	47.2 ± 15.5	865.5 ± 28.3
	Duration (s)	0.13 ± 0.03	0.89 ± 0.07	1.20 ± 0.02	0.12 ± 0.02	0.93 ± 0.02	0.10 ± 0.03	0.98 ± 0.03
Opening	Angular displacement (deg)	349.5 ± 16.5	235.8 ± 62.7	122.4 ± 13.4	317.3 ± 10.4	129.7 ± 10.4	344.5±14.6	116.5 ± 16.5
	Duration (s)	1.22 ± 0.05	0.47 ± 0.09	0.22 ± 0.01	1.07 ± 0.01	0.22 ± 0.01	1.05± 0.03	0.18 ± 0.03
Total flight	Angular displacement (deg)	485.4 ± 4.5	1158.0 ± 10.5	1522.2 ± 8.3	473.5 ± 2.7	1107.3 ± 9.0	482.9± 6.0	1130.0 ± 9.5
	Duration (s)	1.62 ± 0.03	1.55 ± 0.02	1.59 ± 0.01	1.49 ± 0.01	1.39 ± 0.01	1.41 ± 0.02	1.36 ± 0.03

Table Notes: Angular velocity, Displacement and duration descriptive statistics; mean ± SD. All individual one-way ANOVAs reported significant differences.

**Post Hoc test revealed no significant difference for Participant 1's initial flight phases displacement between the 1½ pike and 4½ tuck and initial flight duration between the 3½ pike and 4½ tuck.*

At the Somersault phase, when performing the more difficult dives average angular velocity significantly increased. Participant 1's peak rotational speed was 1160deg/s for the 4½ tuck somersaults. At this phase, divers increased the amount of time spent in a reduced mass moment of inertia state, with 10-13% of total rotation being completed for the 1½ pike somersaults, 69-77% for the 3½ pike somersaults, and 86% for the 4½ tuck somersaults. These results align with prior data (Sinclair, Walker, & Cobley, 2014) where divers achieved 70-74% of their total rotation in the somersault position for the 3½ pike, and 78- 83% for the 4½ tuck somersaults. Miller (2013) also showed that during the somersault position, the centripetal force for the 3½ pike somersault dive is 6 BW, and 8 BW for the 4½ tuck somersault dive. Collectively, the evidence emphasises the importance of muscular strength to increase the joint flexor torques to maintain the Somersault position in more difficult dives.

As the dive degree of difficulty increased, the time available in the Opening Flight phase reduced, along with a reduction in the amount of rotation achieved. When performing the 1½ pike somersaults, divers dedicated a mean of 74% (1.11 ± 0.09s) of their total flight time to the Opening phase. This significantly reduced to 18% (0.30 ± 0.12s) for the 3½ pike and 4½ tuck somersaults. The opening phase also represents the final time point where divers can adjust their aerial positioning and technique prior to water entry. However, as somersault revolutions increase, the divers' musculoskeletal system is being physically challenged by larger centrifugal forces (Miller, 2013), as a result of the increasing angular velocity within the Somersault phase. During opening, a diver will begin to release from their flexed position, reducing joint flexion torques, and thereby decrease centripetal force that maintains their circular somersaulting motion. But, with the shorter amount of duration in the higher degree of difficulty dives, divers must eccentrically control their opening mechanics to prevent uncontrollable under-rotation or over-rotation. This is necessary not only to produce vertical body alignment at water entry, but also prevent injury.

Findings also highlighted that the total time of flight decreased from the 1½ to 3½ pike somersaults. Multiple prior studies (e.g., Sanders & Wilson, 1988) have highlighted that the takeoff posture leans further towards the water in the more difficult forward pike dives. As the springboard recoils from depression, kinetic energy is returned to the diver and is transformed to both the vertical translation and rotation of flight, and so if there is greater forward lean, the ratio of kinetic energy transformed to rotation increases; thus reducing translational energy, resulting in less vertical velocity and consequently flight time. While Total Flight duration decreased from 1½ to 3½ pike somersault dives, a significant increase in Total Flight duration was found between Participant 1's 3½ pike and 4½ tuck somersault dive. As explained in the discussion about the Initial Flight of the 4½ tuck somersault dive, the increased duration may be facilitated by a more upright takeoff posture for dives performed in a tuck position (Miller & Sprigings, 2001) and the angular deceleration apparent immediately after takeoff for the 4½ tuck somersault dive (Figure 4). Delaying the development of angular velocity keeps the body more upright, potentially allowing more energy from the board to be transformed into translational kinetic energy resulting from increase vertical velocity. This would permit the greater air time required to complete the additional somersault revolution.

IMUs and findings from Part 2 highlight some clear implications. When compared to two-dimensional and three-dimensional optical systems, IMUs provide a low cost, light weight, small size, and portable alternative to assessing human movement (Brunetti et al., 2006; Gouwanda & Senanayake, 2008). IMUs provide an opportunity for sports scientists to capture, analyse and evaluate springboard diving performance with greater time efficiency; possible within a 2-3 hour period as was the case here. The current IMU utilised was shown to provide valid and accurate data, with very acceptable marginal error, when compared to a lab-based optical system. IMUs are an emerging tool for movement analysis, and have previously been used to assess and classify the type of somersaults performed in trampoline routines (Helten et al., 2011) and in the snowboard half pipe (Harding et al., 2008). The current IMU's clearly helped illustrate the change in angular velocity time-series plots as somersault revolutions increased, and provided the opportunity to technically analyse dive characteristics and identify areas where performance could be optimised. For instance, based on our data, Participant 2 was the least successful in completing the required somersault revolutions (3.5) for the 3½ pike somersaults (1107°), and initial modelling can help isolate areas for technical modification and skill improvement.

In more difficult dives, it is common for divers to begin to rotate prior to takeoff; and 81° of rotation has previously been observed in divers at the takeoff of the 3½ pike somersaults (Walker et al., 2014). Divers can also continue to rotate through the water after hand entry (Miller, 2013). These tendencies are also relevant to the case of Participant 2, where if potential rotation pre-takeoff is included, data indicated a current capability to generally perform only 3.3 somersault revolutions (1188°). However, two simple simulation models (i.e., one on angular velocity and one on Total Flight time) illustrate how this performance outcome can be improved. Specifically, an estimated 2% increase in either angular velocity or total flight duration would provide an additional 22° of angular displacement, resulting in 3.4 somersault revolutions (1210°). As the diver continues to rotate through the water, 3.4 revolutions is also acceptable in preventing over rotation after hand entry. On the basis of such information, coaches and sports scientists may thus consider either technical (movement coordination) or possible strength and conditioning approaches that target Participants 2's energy return - in terms of linear translation and rotation - from the springboard to improve angular velocity and flight time.

There are several limitations to acknowledge from Part 2 of this study. For instance, data reflects the dive flight kinematics of only three skilled participants; though it is important to consider that there are relatively few skilled high-performing springboard divers (Barris et al., 2012). This study did have access to a limited few of these individuals. Sample size was mitigated by increasing the number of trials per dive and per participant than previously reported (Miller & Sprigings, 2001; Sanders & Gibson, 2000; Sanders & Wilson, 1988). These repeated measures are also of more practical relevance, as coaches in the diving context assess and develop the performance capabilities of individual divers. Still, there should be caution in extrapolating and generalising findings, as present data may reflect idiosyncratic kinematic dive patterns (i.e., atypical). To more conclusively identify the key characteristics and patterns associated with performing highly difficult dives, further analyses are recommended using IMUs. Angular velocity time series plots assessing the consistency and variability in angular displacement and durations in flight phases will likely be helpful in such future analyses.

Conclusion

In Part 1 the accuracy of IMU gyroscopes was validated. Linear regression analysis comparing a 3D optical system and gyroscope output data produced a calibration formula. The application of the calibration formula resulted in mean percentage differences of 0.5% for angular velocity and 0.9% for change in angular displacement between the two systems, indicating that the IMeasureU® IMU provided accurate angular velocity data. In Part 1 the accuracy of IMU gyroscopes was validated. Linear regression analysis comparing a 3D optical system and gyroscope output data produced a calibration formula indicating that the IMeasureU® IMU provided accurate angular velocity data. Mean percentage differences between systems were within 0.5% for angular velocity and 0.9% for change in angular displacement. Part 2 demonstrated the practical application of IMUs to springboard diving. In conjunction with video recording, IMUs helped identify incremental changes in angular velocity (451deg/s - 1090deg/s), angular displacement (473° - 1522°), and concomitant reduction in flight durations (1.62s - 1.36s) according to increasing degree of dive difficulty.

Using angular velocity time series plots, findings identified likely associated characteristics required to perform highly difficult dives. Performance of the 4½ tuck somersault began with a distinct rotational pause immediately after takeoff, likely associated with the need to increase vertical takeoff velocity, and increase total flight time to complete the additional somersault revolution. When performing both the 3½ pike and 4½ tuck somersault dives, the increase in angular velocity likely requires greater concentric muscle effort to maintain the somersault position and greater eccentric control during Opening deceleration phase to prevent under/over-rotation on water entry. Together, parts 1 and 2 highlight how IMU's can be effectively utilised and integrated into contexts such as springboard diving for performance analysis and optimisation purposes.

References for this chapter are included in the list of references at the end of this thesis

CHAPTER 4

Movement variability of springboard divers' flight during multiple forward somersaulting dives

The following chapter was formatted for submission to *Sports Biomechanics*

Author contribution statement

As a co-author on the paper presented within this chapter entitled "*Movement variability of springboard divers' flight during multiple forward somersaulting dives*", as well as being Primary Supervisor throughout the Doctor of Philosophy candidature of Cherie Walker, I confirm Cherie's contribution to the paper as follows:

- Conception and design of the research
- Data collection
- Analysis of data and interpretation of the findings
- Writing the paper and critically appraising content within the manuscript

Signed: Date: 11/08/16

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Movement variability of springboard divers' flight during multiple forward somersaulting dives

By

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Abstract

In springboard diving, movement variability may reflect both unwanted and wanted (functional) adaptation in an effort to enter the water vertically. Three elite springboard divers were examined over four training sessions using IMUs and video recordings to assess the effect of variability in flight kinematics and its effect on water entry. Findings identified that as dive degree of difficulty increased, kinematic within-participant variability decreased in the Somersault phase. Conversely, kinematic variability at the Opening phase increased. Divers seemingly functionally adapted their angular velocity to maintain more consistent Total Flight measures, producing consistent Total Flight angular displacement and durations across all dives (0.5-2.1%). Various kinematic variables measured during flight (e.g. angular displacement during the somersault and angular velocity on water impact) were correlated with entry posture, though with idiosyncratic patterns. Body alignment on during the entry phase correlated with Total Flight angular displacement for the more complex dives, revealing that body alignment was susceptible to minor variations within the amount of total rotation achieved.

Key words: kinematics, gyroscope, angular velocity, dive entry, acrobatics

Movement variability of springboard divers' flight during multiple forward somersaulting dive

Introduction

In springboard diving, a determining factor of successful performance is the skill and aesthetics of dive flight, rotation, duration and vertically aligned entry posture (FINA, 2014). Variations or deviations within either of these elements can subsequently affect performance evaluations by judges. The final element considered by judges is water entry, where divers are aiming to create a 'rip' (no splash) entry which leads to a higher overall dive score (Brown, Abraham, & Bertin, 1984; Driscoll, Gaviria, & Goodwill, 2014; Qian, Zhang, & Jin, 2010). Unwanted variation and deviation from the theoretically possible 'ripped' entry dive is the ever constant target in diving performance. To help optimise performance and attain such a dive, it is important to understand the key biomechanical and kinematic elements required and to accurately determine a diver's capability to execute and control a given required movement pattern; the latter also being important for determining a diver's skill level and readiness for attempting more difficult dives.

Some of the fundamental premises of motor control and learning highlight that to effectively coordinate multiple phases of a given movement, the redundant degrees of freedom in the movement system have to be mastered (Bernstein, 1967). Synergies need to be developed to help ensure efficiency in coordination, perceptual-motor sensitivity and responsiveness so as to ensure adaptability during motor execution (Harbourne & Stergiou, 2009). On this basis, movement variability within well learned tasks can be understood as functional, helping athletes adapt to complex dynamic tasks (Bartlett, 2008; Bartlett et al., 2007; Bradshaw et al., 2007; Button et al., 2003; Trezise et al., 2011). Functional adaptability can therefore potentially account for a degree of change in coordination patterns between consecutive trials of similar movements; often in skilled performers (Button et al., 2003). Similar to other athletic contexts, it is likely then that divers can make different subtle movement changes (where possible) within sequential phases of an inter-related movement pattern, accounting and correcting for variability in one movement phase from potentially affecting the consecutive phase (Newell, 1985).

In acrobatic performance, variations in a gymnast's somersault takeoff have been shown to be compensated by functionally changing body postures with respect to the centre of mass during the flight phase (Bardy & Laurent, 1998; King & Yeadon, 2003). By functionally changing body postures during flight, a gymnast is able to increase or decrease their mass moment of inertia, manipulating their rotational speeds and thus the amount of rotation achieved in different portions of flight. Highly skilled gymnasts have also shown greater variations in their body orientation during the unfolding (opening) of the somersault, and less variation during the final preparatory phase for landing relative to their somersault initiation and position (Bardy & Laurent, 1998). In relation to jump performance, dancers have shown the greatest variability within trunk coordination patterns during descent to correct segmental over-rotation during flight (Smith et al., 2011). For both gymnasts and dancers, it is suggested that such movement variability at particular time points in the movement sequence plays a functional role in helping control and acquire safe landings along with ascertaining successful performance outcomes.

Safe landings in gymnastics or dance can be considered similar to a vertically aligned body posture in 'head-first' diving water entry. Here we can isolate where divers are able to skilfully functionally adapt their multiple flight phases to produce the task constraint of a vertically alignment during water entry (FINA, 2014). Preliminary movement variability data (Coefficient of variation; CV%) has shown that a relatively consistent total angular displacement (0.9±0.2%) can be achieved with different magnitudes of variability in the Initial

Flight (2.5±1.0%), Somersault (1.7±0.8%) and Opening (8.8±4.1%) phases (Sinclair et al., 2014). When in the somersault position, springboard divers' angular velocity has also been shown to be highly consistent during dry land (0.6-1.7%) and aquatic (0.5-1.0%) training environments (O'Meara, 2010; Sinclair et al., 2014). Slobounov et al. (1997) did report that elite springboard divers were able to explore, utilise and control the biomechanical degrees of freedom available, producing a more consistent takeoff approach for dives of higher degrees of difficulty. However, the assessment of a diver's ability to control and adapt to movement variability during aerial phases of dives and the effect of movement variability on a divers water entry has yet to be fully determined. A further limiting factor in prior diving related studies has been the number of trials obtained per participant. Thus, to better examine whether variability is functional and acquired via learned responsive coordination, an increased number of trials per participant needs to be considered for more conclusive interpretations.

Based on the prior literature highlighted and propositions for skilful function movement adaptation, the primary aim of this study was to assess how within-participant movement variability during different phases of dive flight effected a diver's water entry when performing multiple somersault dives from the 3m springboard. The amount of rotation achieved in Total Flight was hypothesised to significantly correlate with the closeness of achieving an extended and vertical body alignment throughout water entry. A secondary aim was to identify whether divers used functionally adaptive strategies to control the amount of rotation achieved within flight phases. With acrobatic literature identifying increased variability during preparatory phases for landing (Bardy & Laurent, 1998), we hypothesised that for highly skilled divers increased variability would occur at the 'opening' preparation phase for water entry, reflecting intentional functional technical movement adjustment and correction. With Slobounov et al. (1997) reporting decreased variability during the forward somersaulting dive running approach as dive degree of difficulty increased, it was also hypothesised that dive flight kinematic variability would decrease as dive degree of difficulty increased. Similarly, we predicted that the greatest decrease in variability would occur at the somersault phase.

Methods

Participants

Following institution ethical approval and consent, three elite springboard divers (one male and two females) participated in the study (age: 21.3±4.7years; height: 1.64±0.07m; mass: 60.1±6.2kg). All participants were injury free and were involved in intensive training at the time of data collection, adhering to ten training sessions per week, and were capable of performing an international standard dive list (Diving Australia, 2016).

Procedures and Experimental Set-Up

Wireless inertial measurement units (IMU; IMeasureU®, Auckland, New Zealand) were used to assess angular velocity during the flight phase of a given forward dive category and across dives of increasing difficulties. The chosen units had a sample frequency of 100Hz, were small in size (22 mm x 34 mm x 10 mm), lightweight (12g) (Finch, Lintern, Taberner, & Nielsen, 2011) and non-distracting to divers. Prior accuracy assessment between the IMUs' gyroscope output measures and three-dimensional motion analysis capture (Cortex 3.3 Motion analysis Corporation, USA) reported a mean angular velocity percentage difference of <0.5% and minimal drift associated with integrating the IMU angular velocity signal (<1.0% difference) (Walker, Sinclair, Graham & Cobley, 2016). Secondary to IMUs, a high-speed Casio Exilim EX-FH100 camera was placed level with and perpendicular to a 3m springboard. The camera was set to a 120Hz frame rate and a shutter speed of 1/250s, with field of view encompassing the dive approach, dive flight, and water entry.

Data were collected in three or four of the divers' regular training sessions to obtain an increased number of trials per dive degree of difficulty. Following a standard dry land warm up, two IMUs were adhered bilaterally to the posterior superior iliac spine (PSIS) using double sided tape and secured with adhesive clear tape (OpSite™ Flexigrid). This minimised the relative motion of the IMUs with respect to the PSIS skin artefacts (Forner-Cordero et al., 2008). Two IMUs were applied as precaution in case one became dislodged during training. IMUs did not dislodge at any time and signal outputs were in agreement. Dynamic sports tape (Rocktape) was also applied to clearly identify on video footage the lateral malleolus of the fibula, greater tubercle of the humerus and middle iliac crest

Divers, with coaches present, were instructed to perform their regular aquatic training routine. In commencing a dive, participants were instructed to stand stably on the springboard for 2-3s, followed by a tap to the IMU prior to initiating a dive approach. This created a clear spike in the gyroscope data allowing it to be synchronised with video footage.

The forward dives performed and number of trials recorded for each participant are summarised in Table 4. Participant 1 performed three dives with differing degrees of difficulty; with his highest degree of difficulty dive (4½ tuck somersault dive) currently the hardest dive performed by male divers internationally. Participants 2 and 3 performed two dives with differing degrees of difficulty, with their highest dive (3½ pike somersault dive) currently the hardest dive performed by females internationally.

Table 4. Individual dive list during record aquatic training sessions.

Participant	Dive	*n*
1	1½ somersaults pike (103B)	5
	3½ somersaults pike (107B)	8
	4½ somersaults tuck (109C)	6
2	1½ somersaults pike (103B)	8
	3½ somersaults pike (107B)	10
3	1½ somersaults pike (103B)	11
	3½ somersaults pike (107B)	13

Table Notes: n is the number of recorded and analysed dive attempts per dive degree of difficulty

Data Analysis

A custom made Matlab script (The MathWorks, Inc., Natick, MA, USA) extracted data for each of the dives performed. Gyroscope data relevant to the somersault axis were then examined in Excel (Microsoft Corp, Redmond, Washington, USA). Time zero was set as the takeoff (i.e., the last frame the divers' feet were on the springboard) for each trial. A majority of the takeoff events were identified via the synchronisation between IMUs and video footage. However, in some cases where a tap to the IMU was not performed before dive approach initiation (i.e., the diver forgot), the angular velocity plots were visually overlayed to match the takeoff event pattern. Pilot testing with trials that did contain the synchronisation signal revealed that the visual alignment process had a maximum error of 0.02s, with a mean of 0.01s for takeoff identification.

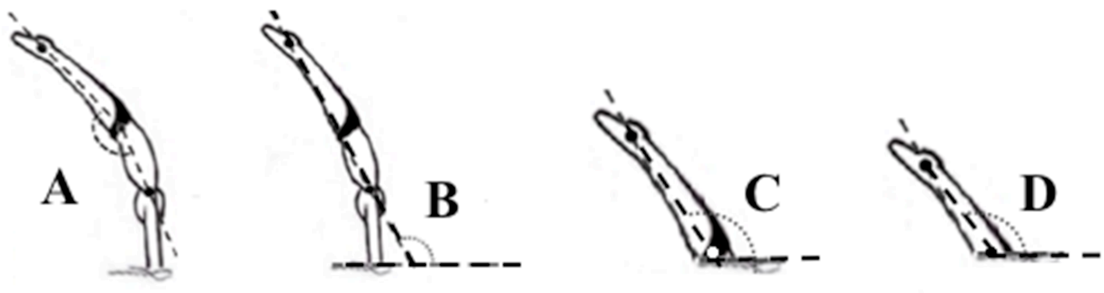
Dive flight was broken down into three phases: Initial Flight, Somersault and Opening (Table 5). Key flight phases were identified through video footage and time synchronised with the IMU angular velocity time series data. Mean angular velocity of the Somersault phase was calculated to represent the rotational speed of each dive. Trapezoidal integration of angular velocity calculated the change in angular displacement (i.e., the amount of rotation achieved) during Initial Flight, Somersault and Opening phases, as well as the angular displacement during the Total Flight of individual dives. The duration of each dive flight phase and total dive flight were also calculated.

Table 5. Definition of the movement phases and the kinematic variables calculated during these phases.

Dive flight phase Kinematics variables	**Definition of the phase**
Total flight Displacement (deg) and duration (s)	Defined from final frame of foot contact with the springboard (takeoff) to the first frame where hands broke the water on entry (Sanders and Gibson 2000).
Initial flight Displacement (deg) and duration (s)	Defined from takeoff to the first frame where the diver's hands touched their legs to form the somersault position
Somersault Angular velocity (deg/s), Displacement (deg), duration (s)	Defined from the somersault position to the first frame where the diver's hands left their legs.
Opening Displacement (deg) and duration (s)	Defined from the somersault open to the first frame where the diver's hands break the water.

To determine and calculate entry phase angles (Figure 11), anatomical land marks were digitised using Tracker software (Brown, 2008). The *x* and *y* pixel coordinates during the entry phase were converted to real world measures via two-dimensional DLT parameters (Reinschmidt & Bogert, 1997). The chosen 3m springboard acted as its own linear reference with 0.4m increment markers along the *x* axis: 0.000m, 0.400m, 0.800m, 1.200m, 1.600m and a known height of 3.000m (*y* axis). The two-dimensional DLT was based on a calibration frame which was scaled to the known position of the chosen 3m springboard and coordinate calculation equations (Walton, 1981).

Figure 11. Water entry events and angles calculated at these events



[1A] **Hip angle**; Calculated as the relative angle between the lower limb and trunk segments (where the knee angle was extended in all cases) at the first frame where the hands broke the water.

[1B] **Body alignment on hand entry**; Calculated as the absolute angle between the line of the lateral malleolus and greater tubercle of the humerus with respect to the right hand horizontal (Sanders & Gibson, 2000) at the first frame where the hands broke the water

[1C] **Body alignment on hip entr**y; Calculated as the absolute body angle between the line of the lateral malleolus and iliac crest with respect the to right hand horizontal at the last frame where the middle iliac crest was visible before water entry

[1D] **Body Alignment on knee entry**; Calculated as the absolute body angle at the between the line of the lateral malleolus and lateral epicondyle of the femur with respect to the right hand horizontal at the last frame where the lateral epicondyle was visible before water entry

Statistical Analyses

Participant mean (X) and standard deviation (SD) were calculated for kinematic variables during dive flight and entry according to each level of dive degree of difficulty. Dive flight variance from trial to trial was represented by each individuals coefficient of variation percentage (CV% = SD/X*100) (Hopkins, 2000).

To assess changes in the relative hip angle and body alignment during the entry phase according to dive degree of difficulty, multiple one-way ANOVAs with repeated measures were conducted using each diver's individual data set (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp). Bonferroni adjustments were applied to minimise the risk of Type I errors. Pairwise comparisons isolated the location of differences between Participant 1's dives in the three dive types. The change in each diver's' body alignment between the hand, hip and knee entry event were also assessed using one-way ANOVAs with repeated measures; again Bonferroni adjustments applied to minimise the risk of Type I errors. Pairwise comparisons isolated the location of differences between the three events of the entry phase. Cohen's d was calculated to represent the effect size of the findings for the entry angles and were interpreted as small, moderate, large, very large and extremely large for a d of 0.2, 0.6, 1.2, 2.0 and 4.0 (Hopkins 2010).

To assess the effect of rotational kinematics' variability on entry posture, Pearson's correlations (r) were conducted for each individual diver. Correlations examined relationships between entry angles (relative and absolute angles) and 1) dive flight durations, 2) dive flight angular displacements, and 3) somersault angular velocity for each dive degree of difficulty. For correlations to be considered statistically significant, a $p \leq 0.05$ was set. Body alignment was measured from the right hand horizontal, thus a negative correlation signified that a diver was able to attain an angle closer to the 90° vertical. On the other hand, positive correlations between rotational kinematics and hip angle at hand entry were associated with a more extended hip (closer to 180°).

Results

Angular velocity times-series plots of multiple forward somersault dives illustrated a common shape and pattern of performance for each of the dive degree of difficulty across all participants (Figure 12). Each participant demonstrated an increased consistency in the shape of their curves as dive degree of difficulty increased, with a smaller spread of SD curves from the mean.

Dive flight kinematics according to dive degree of difficulty

Mean dive flight kinematics are presented in Table 6, with coefficients of variation (CV%) representing the level of relative within-participant variability for each kinematic variable. Coefficient of variation demonstrated common trends across the three divers when comparing the performance of their 1½ and 3½ pike somersault dives. Specifically, within-participant variability during the Initial Flight and Somersault phases were lower across all participants 3½ pike somersault dive; while within-participant variability increased for all participants' Opening Flight kinematics during the 3½ pike somersault dive.

Participant 1 was the only diver able to perform the 4½ tuck somersault dive. The variability of his angular displacement during the Initial Flight phase of the 4½ tuck somersault dive was similar to the 3½ pike somersault (Table 6). However, the variability in duration of the Initial Flight phase was higher for the 4½ tuck somersaults (CV = 8.3%). During the Somersault and Opening Flight phases, variability was lower for the 4½ tuck somersault dive across all variables.

Angular displacement and duration of the Total Flight were more consistent than the separate three phases of flight across all dive degree of difficulties. The mean within-participant variability for all variables calculated during Initial Flight, Somersault and Opening phases was 9.4±7.9% for all dive degree of difficulties. The variability in Total Flight kinematics reduced to a mean of 1.0±0.5% across all dives performed (Table 6).

Entry phase kinematics

Upon water entry, all participants were less vertically aligned at hand entry for the 3½ pike somersault dive when compared to their 1½ pike somersault (Participant 1 $p = 0.007$, $d = 2.5$; Participant 2 $p < 0.001$, $d = 7.3$; Participant 3 $p < 0.001$, $d = 5.7$; Table 7). No significant difference was found between Participant 1's 3½ pike and 4½ tuck somersault for entry body alignment ($p = 1.000$, $d = 0.4$). At entry, Participant 2 and 3 were less extended about the hip for the 3½ pike somersault when compared to the 1½ pike somersault dive (Participant 2 $p < 0.001$, $d = 7.1$; Participant 3 $p < 0.001$, $d = 7.1$). Participant 1's entry hip angle was similar for

Figure 12. Angular Velocity time series plots of increasing dive degree of difficulties for participant 1, participant 2 and participant 3. Takeoff is time zero and mean hand entry is the final data point on the time series plot.

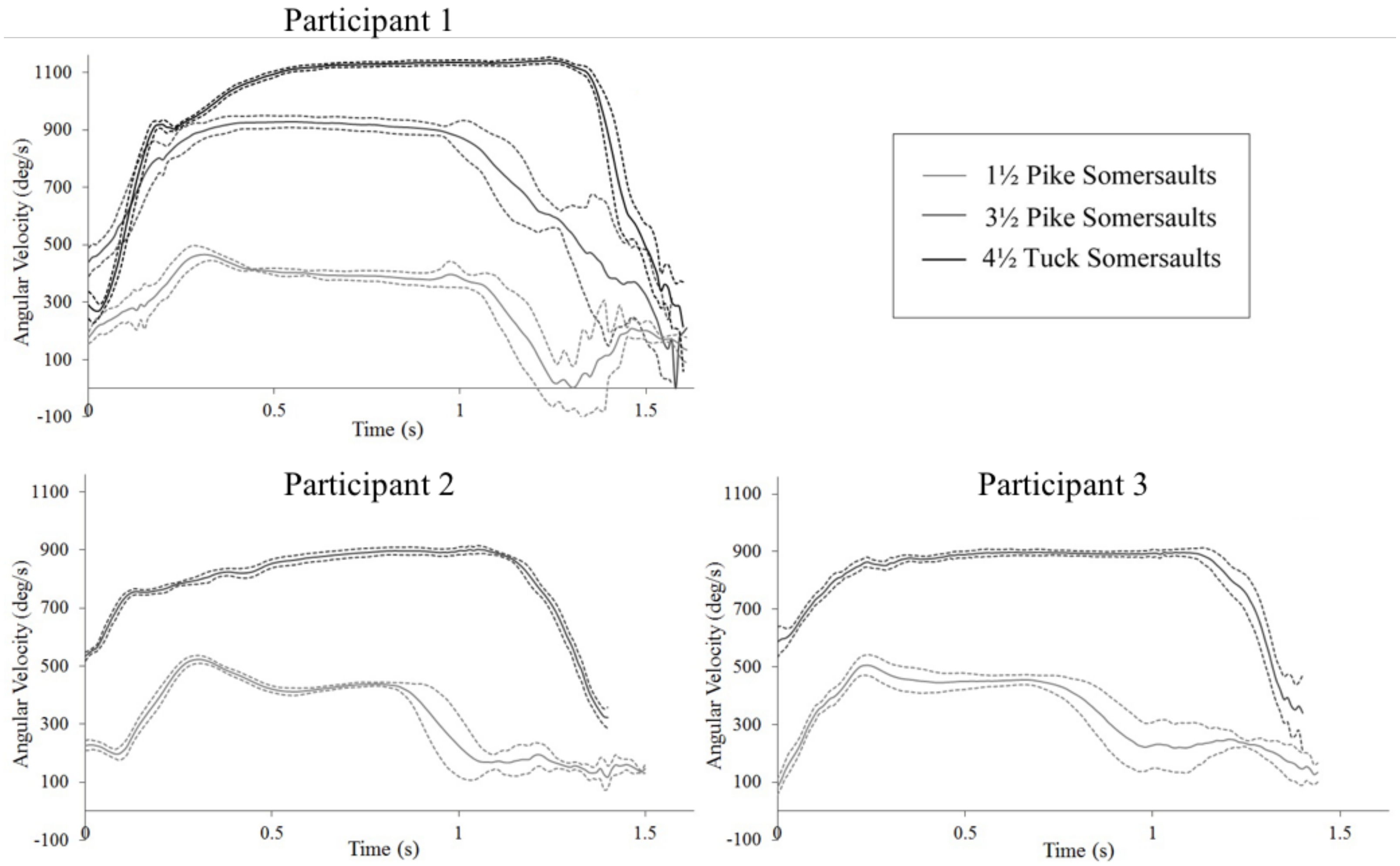


Figure notes: Mean = solid line; ± SD = dotted line

Table 6. Participant dive flight kinematics of forward dives of increasing degree of difficulty. Within-participant variability of dive flight kinematics is presented in parentheses (CV%).

Dive flight phase	Variable	Participant 1			Participant 2		Participant 3	
		1½ pike	3½ pike	4½ tuck	1½ pike	3½ pike	1½ pike	3½ pike
Initial flight	Angular displacement (°)	84.3 (15.8)	123.6 (12.2)	95.0 (12.5)	93.6 (10.0)	171.0 (5.3)	91.2 (14.5)	148.0 (10.5)
	Duration (s)	0.27 (12.8)	0.20 (6.5)	0.17 (8.3)	0.29 (4.9)	0.24 (4.6)	0.26 (10.5)	0.20 (10.2)
Somersault	Angular velocity (deg/s)	451.2 (4.2)	904.5 (2.5)	1090.3 (0.6)	500 (2.5)	865.7 (1.2)	468.1 (9.3)	885.4 (0.8)
	Angular displacement (°)	51.6 (23.4)	822.2 (6.6)	1304.0 (1.4)	62.6 (19.0)	806.5 (1.9)	47.2 (32.9)	865.5 (3.3)
	Duration (s)	0.13 (23.7)	0.89 (7.5)	1.20 (1.6)	0.12 (17.6)	0.93 (1.7)	0.10 (28.4)	0.98 (2.8)
Opening	Angular displacement (°)	349.5 (4.7)	220.9 (26.6)	122.4 (10.9)	317.3 (3.3)	129.7 (8.1)	344.5 (4.2)	116.5 (14.2)
	Duration (s)	1.22 (4.0)	0.47 (18.4)	0.22 (6.1)	1.07 (1.2)	0.22 (6.5)	1.05 (3.2)	0.18 (17.6)
Total flight	Angular displacement (°)	485.4 (0.9)	1158.0 (0.9)	1522.2 (0.5)	473.5 (0.6)	1107.3 (0.8)	482.9 (1.2)	1130.0 (0.8)
	Duration (s)	1.62 (1.6)	1.55 (1.4)	1.59 (0.5)	1.49 (0.8)	1.39 (0.5)	1.41 (1.7)	1.36 (2.1)

the 1½ and 3½ pike somersault dives (*p* = 0.194, *d* = 1.2) as well as the 3½ pike and 4½ tuck somersault dives (*p* = 0.509, *d* = 0.7). Divers continued to rotate through the water, with a more vertically aligned body angle at knee entry when compared to the first frame where the hands broke the water ($p < 0.05$, $d \geq 0.7$ for all participants 1½ and 3½ pike somersaults). However, no significant difference was found between the body alignment at hand, hip or knee entry for participant 1's 4½ tuck somersault dive ($p > 0.05$, $d = 0.9$).

Dive flight and water entry kinematic correlations according to dive degree of difficulty

The effect of rotational kinematics on entry posture demonstrated unique patterns across all three participants dive degree of difficulties (see Table 5, 6 & 7). There were, however, there were common negative correlations between Total Flight angular displacement and body alignment during the entry phase for each divers' most difficult dive (Participant 1 = 4½ tuck somersaults, Participant 2 and 3 = 3½ pike somersaults). Variability within the amount of Total Flight angular displacement achieved affected the absolute body angle on hand, hip and knee entry ($p < 0.05$). Dive performances with greater Total Flight angular displacement resulted in a more vertical alignment throughout the entry phase (closure to 90°).

All participants demonstrated positive correlations ($p < 0.05$) for the entry phase of the 3½ pike and 4½ tuck somersault dive between; 1) the body alignment on hand and hip entry, 2) the body alignment on hand and knee entry and 3) the body alignment on hip and knee entry. This positive correlation suggests that the closer divers were to a vertical body alignment on hand entry, the closer the divers were to a vertical alignment on hip and finally knee entry for the higher degree of difficulty dives.

Table 7. Participant entry posture for increasing forward dive degree of difficulties. Within-participant variability of dive flight kinematics is presented in the parenthesis (CV%).

Dive flight phase	Variable	Participant 1			Participant 2		Participant 3	
		1½ pike	3½ pike	4½ tuck	1½ pike	3½ pike	1½ pike	3½ pike
Relative hip angle (deg)	Hand Entry	177 ± 2	156 ± 23	144 ±14	177 ± 3	111 ± 13 [A]	169 ± 7	103 ±11 [A]
Absolute vertical body alignment (deg)	Hand entry	110 ± 2 [1]	129 ± 11 [1]	133 ± 11	110 ± 3 [1]	159 ± 9 [1, A]	114 ± 3 [1]	160 ± 11 [2, A]
	Hip entry	104 ± 3	113 ± 13	125 ± 11	101 ± 2 [2]	146 ± 10 [2, B]	106 ± 6 [2]	146 ± 14 [B]
	Knee Entry	104 ± 3 [3]	108 ± 7 [3]	123 ± 13 [F]	95 ± 3 [3]	130 ±14 [3, C]	95 ± 7 [3]	128 ± 20 [3, C]

Table Notes: Post Hoc testing revealed ($p < 0.05$)

[1]Significant difference between body alignment angles at hand and hip entry

[2]Significant difference between body alignment angles at hand and hip entry at hip and knee entry

[3]Significant different between body alignment angles at hand and knee entry

[A]Significiant difference between the relative hip angle and absolute body angle on hand entry between 1½ and 3½ pike

[B]Significiant difference between the absolute body alignment on hip entry between 1½ and 3½ pike

[C]Significiant difference between the absolute body alignment on knee entry between 1½ and 3½ pike

[D]Significiant difference between the relative hip angle or absolute body angle on hand entry between 3½ pike & 4½ tuck somersault

[E]Significiant difference between the absolute body alignment on hip entry between 3½ pike and 4½ tuck somersault

[F]Significiant difference between the absolute body alignment on knee entry between 3½ pike and 4½ tuck somersault

Table 8. Pearson's correlation (r) between entry posture and dive flight variables for forward 1½ pike somersaults by all participants. Correlation coefficients are calculated separately for each participant; P1, P2 and P3.

	Relative hip angle at hand entry			**Absolute body angle at hand entry**			**Absolute body angle at hip entry**			**Absolute body angle at knee entry**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Initial flight duration	-0.51	0.29	-0.25	-0.09	-0.19	0.56	0.07	0.23	0.44	0.29	0.50	0.39
Somersault duration	-0.05	-0.39	0.29	-0.31	-0.10	-0.74*	-0.54	-0.19	-0.65*	-0.77	-0.36	-0.72
Opening duration	0.86	0.24	0.11	0.04	0.49	0.05	0.12	0.29	0.07	0.10	0.29	0.07
Total flight duration	0.94*	-0.11	0.16	-0.36	0.12	-0.13	-0.28	0.24	-0.13	-0.31	0.26	-0.26
Initial flight angular displacement	-0.82	0.71*	-0.10	0.21	-0.14	0.35	0.33	0.08	0.21	0.53	0.37	0.21
Somersault angular displacement	0.05	-0.31	0.37	-0.42	-0.05	-0.57	-0.42	-0.14	-0.57	-0.23	-0.29	-0.56
Opening angular displacement	0.86	-0.35	-0.17	0.04	0.12	-0.03	-0.44	0.09	0.14	-0.34	0.03	0.13
Total flight angular displacement	0.87	-0.21	0.32	-0.36	-0.24	-0.80*	-0.31	0.01	-0.67*	-0.29	0.10	-0.68*
Somersault angular velocity	0.68	0.41	0.57	0.45	-0.06	-0.14	0.39	-0.39	-0.30	0.44	-0.51	-0.03
Relative hip angle at hand entry				-0.24	-0.35	-0.52	-0.23	-0.34	-0.78*	-0.35	-0.23	-0.44
Absolute body angle at hand entry							0.97*	0.85*	0.92*	0.80	0.67	0.95*
Absolute body angle at hip entry										0.92*	0.92*	0.86*

Table Notes: Table Notes: Correlation coefficients are calculated separately for each participant; P1, P2 and P3.
** Represents a significant correlation for an individual participant (p < 0.05).*

Table 9. Pearson's correlation (r) between entry posture and dive flight variables for forward 3½ pike somersaults by all participants

	Relative hip angle at hand entry			**Absolute body angle at hand entry**			**Absolute body angle at hip crest entry**			**Absolute b e at knee entry**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Initial flight duration	0.05	0.01	0.24	-0.24	0.57	-0.05	-0.26	0.56	0.08	-0.30	0.63	0.03
Somersault duration	0.00	-0.32	-0.04	-0.18	0.02	-0.18	-0.16	-0.85*	-0.32	-0.15	-0.06	-0.20
Opening duration	-0.02	0.21	0.56*	0.20	-0.56	-0.33	0.16	0.22	-0.22	0.09	-0.46	-0.31
Total flight duration	0.09	-0.32	0.77*	-0.02	-0.20	-0.59*	-0.19	-0.48	-0.50	-0.43	-0.07	-0.52
Initial flight angular displacement	0.43	0.13	0.28	-0.58	0.51	-0.11	-0.59	0.88*	0.02	-0.78*	0.57	-0.08
Somersault angular displacement	0.30	0.16	-0.18	-0.50	-0.44	-0.09	-0.04	-0.86*	-0.25	-0.39	-0.60	-0.12
Opening angular displacement	-0.49	-0.01	0.34	0.65	-0.56	-0.12	0.61	-0.26	-0.01	0.60	-0.39	-0.06
Total flight angular displacement	-0.78*	0.39	0.51	0.59	-0.88*	-0.64*	0.63	-0.89*	-0.71*	0.47	-0.91*	-0.58*
Somersault angular velocity	0.72*	0.53	-0.47	-0.65	-0.76*	0.13	-0.57	0.08	-0.05	-0.48	-0.84*	0.07
Relative hip angle at hand entry				-0.91*	-0.09	-0.88*	-0.95*	-0.29	-0.81*	-0.75*	-0.24	-0.86*
Absolute body angle at hand entry							0.93*	0.93*	0.96*	0.93*	0.96*	0.93*
Absolute body angle at hip entry										0.89*	0.96*	0.95*

Table Notes: Correlation coefficients are calculated separately for each participant; P1, P2 and P3.
** Represents a significant correlation for an individual participant (p < 0.05).*

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Table 10. Pearson's correlation (r) between entry posture and dive flight variables for forward 4½ tuck somersaults by Participant 1.

	Relative hip angle at hand entry	**Absolute body angle at hand entry**	**Absolute body angle at hip crest entry**	**Absolute body angle at knee entry**
Initial flight duration	-0.32	0.35	0.56	0.57
Somersault Duration	0.22	-0.91*	-0.85*	-0.86*
Opening Duration	0.36	0.42	0.22	0.28
Total flight duration	0.49	-0.67	-0.48	-0.33
Initial flight angular displacement	-0.44	0.78	0.88*	0.86*
Somersault angular displacement	0.24	-0.94*	-0.86*	-0.86*
Opening Angular displacement	0.05	-0.01	-0.26	-0.29
Total flight angular Displacement	-0.02	-0.86*	-0.89*	-0.98*
Somersault angular Velocity	0.05	0.35	0.08	0.07
Relative hip angle at hand entry		-0.35	-0.29	-0.08
Absolute body angle at hand entry			0.93*	0.90*
Absolute angle at hip entry				0.96*

*Table Notes: * Represents a significant correlation for an individual participant ($p < 0.05$).*

Discussion and Implications

The current study examined the effect of within-participant rotational kinematic variability on water entry when performing forward dives of increasing difficulty. Each participant presented their own unique correlations, with a larger number of significant correlations for the highest degree of difficulty dive performed by each participant. The increased number of significant correlations between dive flight kinematics and entry angles demonstrates that divers need to control a greater number of elements during dive flight for more difficult dives to achieve required end-point water entries. This is supported by the fact that absolute variability (CV%) reduced for the Somersault phase of dive flight. The increased consistency during each participant's more difficult dive may be the result of increased rotational demands required, and therefore less available time for movement error. Angular velocity time-series plots (Figure 2) illustrated the increased consistency with less spread of values within the SD curves for the Somersault phase. Relative variability (SD) ranged between 6.9-10.7deg/s, reflecting a difference of <1.0% of Total Flight angular displacement achieved during this phase. Despite consistent angular displacement across Total Flight, divers did become less vertically aligned on water entry for the 3½ pike and 4½ tuck somersault dives. These findings combined highlight the technical importance of maintaining a tight somersault position to prevent angular velocity deceleration and help ensure adequate rotation is achieved prior to water entry preparation. In fact, the hypothesised correlation between Total Flight angular displacement and body alignment at entry ($p < 0.05$) across each diver's most difficult dive supports the importance of developing sufficient angular momentum prior to take-off (Hamill, Ricard, & Golden, 1986) to then be able to functionally adapt the timing and rate of deceleration to achieve the required amount of rotation to permit a more vertically aligned water entry.

Related to both study aims we also wanted to address whether and where divers used functional adaptive strategies to manipulate the amount of rotation achieved during phases of multiple forward somersaulting dives. We postulated that Opening Flight phase variability would increase as dives became more difficult. Results show that coefficients of variations for angular displacement and duration did increase from the 1½ and 3½ pike somersault; and were greater for the 4½ tuck somersault dive when compared to the 1½ pike somersault dive. Based on these findings, we suggest that adaptive strategies were utilised at during the final phase of the dive flight. Similar to studies of gymnasts (Bardy & Laurent, 1998; Lee et al., 1992; Yeadon & Hiley, 2014), it is proposed that increases in variability are a response to the amount of rotation achieved during the Initial Flight and Somersault phases of dive flight, as well as the environmental constraint of time to contact with the water. According to the dynamical systems theory, variability during the opening phase can be viewed as a compensatory factor that permits divers to explore the task and environmental constraints imposed on them in order to acquire stable performance outcomes (Glazier et al., 2003; Newell, 1986).

Variability within the Opening flight reflects a flexible movement pattern (Harbourne & Stergiou, 2009), where adjustments to the duration of the Somersault phase and rate of angular deceleration during Opening are made. These adjustments may be according to a feedback control strategy (Hiley, Zuevsky, & Yeadon, 2013; Yeadon & Hiley, 2014). Feedback control is most likely occurring via prospective control, where sequential temporal movement, potentially alongside visual cues (i.e via "spotting") across dive flight, provide information for estimated time to water contact (Bardy & Laurent, 1998). Such feedback, coupled with a learned sense of timing and capability to skilfully adapt movement, may permit divers to produce highly consistent Total flight angular displacements (0.5-0.8%) for the more complex 3½ pike and 4½ tuck somersault dives.

Implications

When considered together, the general pattern of findings across divers and correlations within-divers provide direct implications for coaches and sports scientists for individualised skill acquisition, training and performance optimisation. For instance, correlations between the Somersault phase (angular velocity, displacement and/or duration) and entry angles for Participant 1 and 2 highlight the importance of strength training to resist high centrifugal forces (Miller, 2013), improve the maintenance of a tight somersault position, and subsequently functionally reduce mass moment of inertia. Participant 2's lower angular velocity, when compared to other divers, also suggests that training focusing on the technique and strength required to develop adequate angular momentum at the springboard approach and take-off would be beneficial. Meanwhile, Participant 3's correlations suggest flight duration was a constraining factor in the 3½ pike somersaults, again implying the need to improve springboard approach and take-off. The development of lower limb strength to improve both linear and angular momentum on take-off would also seem beneficial (Hamill et al., 1986; Sanders & Wilson, 1988).

Limitations

While noting the small number of participants in this study, it should be recognised that this study intentionally deployed a within-participant as well as between participant research design and analysis to address study purposes. This study focused on the idiosyncratic characteristics of movement variability in angular velocity, angular displacement and flight phase durations. To help address sampling concerns, an increased number of dive trials per participant and according to dive type were conducted than previously reported. The sample also assessed elite divers which are themselves rare (Barris, 2013) and unique (Bates, 1996), but provide appropriate models for examination given study purposes. As intimated by our research and analysis, findings cannot be readily extrapolated to other divers of similar or different skill levels as present data could potentially reflect idiosyncratic kinematic dive patterns. That said, our methods and analytical approach provide methods for how sport scientists and practitioners can more accurately assess movement techniques of other divers; how areas of present skill and technical limitation can be identified; and, how targeting areas of limitation may optimise performance.

Conclusion

The present study identified that as dive degree of difficulty increased, within-participant movement variability became smaller for Somersault phase kinematics. Such adjustments were subsequently associated with increases in movement variability at the Opening phase of dives. Such increased variability likely reflects the occurrence feedback control strategy where the timing and rate of angular deceleration is functionally adapted in accordance with events in preceding dive flight phases. Thus, it is suggested that highly skilled divers functionally link and respond to the three phases of flight to achieve consistent angular displacement across Total Flight (0.5-0.9%). However, even with a high degree of consistency for Total Flight within difficult dives, relatively minor variations of Total Flight angular displacement were significantly correlated with body alignment on hand, hip and knee entry. The within and between participant study design helps illustrate how examining and tracking an individual's technique and functional adaptation characteristics can be valuable for performance optimisation.

References for this chapter are included in the list of references at the end of this thesis

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CHAPTER 5

Application of functional data analysis to characterise the performance of the forward 3 ½ somersault dive from the 3m springboard

The following chapter is formatted for submission to the *Scandinavian Journal of Medicine & Science in Sports*

Author contribution statement

As a co-author on the paper presented within this chapter entitled "*How functional data analysis can help more finitely characterise between and within technical movement variability: Insights from springboard diving"*, as well as being Primary Supervisor throughout the Doctor of Philosophy candidature of Cherie Walker, I confirm Cherie's contribution to the paper as follows:

- Conception and design of the research
- Data collection
- Analysis of data and interpretation of the findings
- Writing the paper and critically appraising content within the manuscript

Signed: Date 11/08/16

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Application of functional data analysis to characterise the performance of the forward 3½ pike somersault dive from the 3m springboard

By

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Abstract

Measuring and evaluating the biomechanical and technical skill characteristics of entire movement sequences within sport contexts (e.g., springboard diving) has historically been hindered by methodological and technological limitations. Discrete kinematic measures have been common, but with less continuous analysis of variables. Thus, using functional principal component analytical (*f*PCA) procedures, the purpose of this paper was to examine structural differences and magnitude of movement variability for two divers, of different skill levels (one National and one International level), when performing the forward 3½ pike somersault dive. Findings identified that five *f*PC explained 96.5% of the variability within repeated measures of angular velocity curves. The National diver's scatter plots and *f*PCs scores standard deviations presented larger magnitudes of variability within her angular velocity movement sequence, in particular for *f*PC1 and *f*PC3, where the magnitudes of variability (SD) were 282.6 for *f*PC1 and 201.5 for *f*PC3. The international diver presented structural features indicative of a more consistent movement pattern with notable clusters of scores for her *f*PCs (e.g., *f*PC1 SD = 75.2 and *f*PC3 SD = 68.0). The random nature of the National diver's variability was associated with a reduced capacity to link the multiple phases of the complex aerial sequence, while the International diver's variability was likely associated with functional feedback back strategies in response to the initiation of the somersault position. This study presents the potential of *f*PCA to examine repetitive technical movement characteristics of skilled performers, with potential to monitor the unique nature and development of athletes.

Key words: Biomechanics, Acrobatics, Skill Acquisition, Movement Variability, Expertise, Principal Component Analysis.

Application of functional data analysis to characterise the performance of the forward 3½ pike somersault dive from the 3m springboard

Introduction

Springboard diving is an individual sport that requires athletes to perform complex aerial manoeuvres before entering into the water. Currently the most difficult forward category dive performed internationally by females is 3½ somersaults in a pike position. Previous research examining the characteristics and requirements of this dive have used discrete kinematic measures (e.g., mean takeoff posture), with particular emphasis on how the linear translation and rotational aspects are developed during the springboard approach (Miller, 1984, 2013; Miller & Munro, 1985b; Miller & Sprigings, 2001; Sanders & Gibson, 2000). Practical implications have been drawn from the use of such discrete measures, however at the same time due to prior methodological and technological limitations, large amounts of potentially important data are disregarded and subsequent theoretically valuable information may be missed (Ryan et al., 2006). In the context of measuring human movement, the extraction of discrete measures, may also reduce the full potential available to sports scientists' for analysing the entire movement pattern.

Recent technological advances, in the form of inertial measurement units (IMUs), now provide the capability to collect and analyse human movement in ecologically valid and real performance contexts (Walker et al., 2016). Specifically, in springboard diving, IMUs have provided continuous time-series angular velocity data on performances of multiple somersaulting dives (Sinclair et al., 2014; Walker et al., 2015; Walker et al., 2014). Single discrete measures, such as mean angular velocity and change in angular displacement, have been used to statistically compare differences in angular velocity and change in total flight angular displacement according to dive degree of difficulty (Walker et al., 2016). However, to gain these measures angular velocity time-series data were reduced to means and standard deviations, ultimately restricting the full scope of continuous time-series data available.

Functional Data Analysis (FDA) has emerged in biomechanics as a contemporary and applicable area of statistics when analysing the pattern and variability of continuous human movement data (Dona et al., 2009; Harrison, Ryan, & Hayes, 2007; Ryan et al., 2006). FDA techniques consider an entire series of data points as a single functional entity, rather than a series of individual data points (Harrision, 2014). One commonly used FDA technique in biomechanics is functional principal components analysis (*f*PCA), where principal components (represented as functions) describe the nature and structure of variability in a series of curves (Ryan et al., 2006). This statistical technique has been used effectively in the evaluation of movement performance differences in a range of sporting contexts. Technical differences have been identified in race walkers of differing skill levels using *f*PCA applied to kinematic (knee angle) and kinetic variables (knee moment) (Dona et al., 2009). Similarly different kinetic time-series have been shown to indicate skill level differences in rowing (force-magnitude and force-angle) and swimming (propulsion force-time) performance using *f*PCA (Sacilotto et al., 2015; Warmenhoven et al., 2015).

The use of functional principal component analysis presents an opportunity to move away from the sole use of discrete measures or qualitative approaches for describing shape characteristics of time-series in somersaulting dives. *f*PCA would allow for a more comprehensive statistical approach that preserves all of the original content from collected time-series data. Understanding what patterns of variability are present in angular velocity time-series is important for accurate characterisation of dive performance and quantification of skill level for individual athletes. At present, research using FDA strategies in sports biomechanics have attempted to understand performance or skill differences in sporting movements through the assessment of "between-athlete" differences in the structure of movement patterns (i.e. shape changes between athletes in time-series variables) (Dona et al., 2009; Sacilotto et al., 2015; Warmenhoven et al., 2015). In addition to assessing between athlete differences, there is also great potential for the use of *f*PCA in the evaluation of 'within-athlete' variability of movement patterns. In this context, the type and magnitude of variability across particular parts of a functional data sequence could be explored to understand whether differences in within-athlete variability are associated with known performance metrics. This would allow for a better understanding of the functional role of within-athlete variability (Bartlett, 2008) in skilled sporting movements.

Using the novel application of *f*PCA analytical procedures, the purpose of this paper was to more finitely examine the repetitive technical movement characteristics of the forward 3½ pike somersault dive, with aim to evaluate the differences in the structure (between-athlete) and magnitude (within-athlete) of variability between two highly skilled divers of differing competition experience levels: National and International. We expected there to be differences between the divers' continuous angular velocity movement patterns and thus it was hypothesised that the National level diver would be associated with a greater magnitude of variability. We accounted for the reduced variability in the International diver to be related to the development of coordination linkages between several phases of dive flight.

Methods

Participants

Springboard diving is predominantly an individual sport, with a small number of athletes within Australia being able to complete the current international standard dive list. Currently within Australia there are only five female athletes who are able to perform the 3½ pike somersault dive. Following institution ethical approval and consent, two highly skilled female springboard divers (age = 19.0±4.2years; height = 1.64±0.05m; mass = 56.7±2.3kg) capable of performing the 3½ pike somersaults participated. Participant 1 was a FINA internationally ranked diver, while Participant 2 was a nationally ranked junior elite diver. The International diver had two years of experience performing the forward 3½ pike somersault dive, while the National diver had been performing this dive for one month prior to data collection. Both divers were injury free and completing intensive training at the time of data collection, adhering to ten training sessions per week.

Procedures and Experimental Set-Up

Data were collected across three regular sessions for each diver, with an aim to collect multiple repeated trials of the 3½ pike somersault dive. These sessions were in line with the divers regular training and therefore did not interrupt the training routine, i.e. heavy weight sessions were not conducted the morning of the 3m springboard sessions, reducing the potential for muscle fatigue and soreness. Wireless inertial measurement units (IMUs; IMeasureU®, Auckland, New Zealand), with a sample frequency of 100Hz, were used to measure the angular velocity during the flight phase of the forward 3½ pike somersault dive. Prior accuracy assessment between the IMUs' gyroscope output measures and three-dimensional motion analysis capture (Cortex 3.3 Motion Analysis Corporation, USA) reported a mean percentage difference of 0.5%, providing validity to IMU gyroscope angular velocity measures (Chapter 3). IMU units were small in size (22 mm x 34 mm x 10 mm), lightweight (12g) and non-distracting to the divers (Finch et al., 2011). Secondary to the IMUs, a high-speed Casio Exilim EX-FH100 camera was placed level and perpendicular to the chosen 3m springboard. The camera was set to a 120Hz frame rate and shutter speed of 1/250s, with a field of view limited to dive approach, dive flight, and water entry.

At training sessions divers, with coaches present, were instructed to perform their regular dry land warm up and aquatic training routine. Following warm up, two IMUs were adhered bilaterally to the posterior superior iliac spine (PSIS) with adhesive double sided tape and secured with an adhesive film (OpSite™ Flexigrid) to minimise relative motion of the IMU with respect to the PSIS skin artefacts (Forner-Cordero et al., 2008). Two IMUs were applied as a precaution in case one became dislodged during training. Neither became dislodged and the signal outputs were in agreement. Before commencing dives, participants were instructed to stand stably on the springboard for 2-3s, followed by a tap to the IMUs prior to initiating a dive approach. The tap created a clear spike in the gyroscope data and was visible on the video footage, allowing synchronisation. Each performance of the 3½ pike somersault dive was video recorded.

Data Analysis

In total, ten performance trials of the 3½ pike somersault dive were analysed for each participant. A custom made Matlab script (The MathWorks, Inc., Natick, MA, USA) extracted IMU data for each of the dives performed. Gyroscope data relevant to the somersault axis were then examined in Excel (Microsoft Corp, Redmond, Washington, USA). Time zero was set as the takeoff (i.e., the last frame the divers' feet were on the springboard) for each trial. Takeoff events were identified via synchronisation between IMUs and video footage, however in some cases where a tap to the IMU was not performed (i.e., the diver forgot), angular velocity plots were visually overlayed to match the takeoff event pattern. Pilot testing with trials that did contain the synchronisation signal revealed that the visual alignment process had a mean error of 0.01s for takeoff identification. Proceeding takeoff, dive flight was broken down into three phases: Initial flight, Somersault and Opening (Table 11). The key events that defined each phase were identified via video footage and synchronised with the IMU signal. Pilot testing revealed these key events could be identified on the video footage within 0.01s, with a maximum error of 0.02s. The mean of these phases were visually represented on the angular velocity curves.

Data processing

To normalise each of the twenty angular velocity curves to express a 100% of the dive movement sequence (Helwig, Hong, Hsiao-Wecksler, & Polk, 2011), a linear length normalisation strategy using an interpolating cubic spline was applied. Normalisation did not affect the linear compression or expansion of the raw data as the standard deviations for total dive flight time was minimal (1.37±0.03s). Once normalised, the 100% dive movement sequence was divided into the three flight phases.

Table 11. Definition of the dive flight phases.

Dive flight phase	Definition
Total flight	Defined from final frame of foot contact with the springboard, takeoff, to the first frame where hands broke the water on entry (Sanders & Gibson, 2000).
Initial flight	Defined from takeoff to the first frame where the diver's hands touched their legs to form the somersault position
Somersault	Defined from the formation of the somersault position to the first frame where the diver's hands left their legs.
Opening	Defined from the opening of the somersault position to the first frame where the diver's hands break the water.

Functional principal component analysis

A custom made functional data analysis Matlab script (The MathWorks, Inc., Natick, MA, USA) was generated in accordance with available software from a functional data analysis website (http://www.psych.mcgill.ca/misc/fda/). In this script, b-spline basis functions were used for the creation of angular velocity time-series curves. The smoothing parameter was selected using a combination of a generalised cross validation (GCV) procedure (Ramsay &

Dalzell, 1991) and visual inspection of the smoothing parameter. From these smoothed curves, functional principal components (*f*PCs) were derived. Each *f*PC was varimax rotated to allow for an informative evaluation of specified parts of the angular velocity-time curves (Ramsay & Silverman, 2013). Each angular velocity time-series curve was weighted by each of the first five *f*PCs, with the resulting scalars referred to as *f*PC scores. Individual *f*PC scores were calculated by multiplying each data function by the relevant *f*PC and integrating over (0,1) (Donoghue et al., 2008). The occurrence and magnitude (y-axis amplification) of angular velocity variability was graphically represented as individual *f*PC plots, illustrating the mean curve of the angular velocity and two additional curves created by adding (+) or subtracting (-) a multiple of the *f*PC (Dona et al., 2009).

Descriptive statistics and scatter plots were then used to analyse differences in the structure of variability between the individual divers (Dona et al., 2009). Dive performances with positive scores were more likely to resemble characteristics of the '+' curve, while negative scores resembled characteristics of the '-' curve. The intra-athlete standard deviation of *f*PC scores was also calculated for the two divers using scores for each *f*PC. These within-athlete standard deviations were used to assess the magnitude of variability within each *f*PC and compare within-athlete variability between the two divers. To confirm whether the standard deviations of the *f*PC scores represented the magnitude (y-axis amplification) of angular velocity variability, the standard deviation of each diver's angular velocity time-series data were graphically presented as their own function and compared to the spread of the *f*PC scores.

Results

Between-athlete differences in movement pattern structure and the magnitude of within-athlete variability is represented in Figure 13 and Figure 14. Each individual participant's angular velocity time-series standard deviation function (Figure 14) illustrated the same pattern of variability as the *f*PCs and their respective *f*PC scores.

The first five *f*PCs represented 96.5% of variation in the angular velocity data for the forward 3½ pike somersault dive. *f*PC1 accounted for 48% of the total variability within the angular velocity curves (Figure 15). Positive scoring dives for *f*PC1 were indicative of decreased angular velocity during the Initial Flight phase, with that pattern reversing to show faster rotation from approximately 15-35% of the movement sequence. Positive scorers also had increased angular velocity in the final portion of the dive (80-95%), leading to a later initiation of angular deceleration. Negative scorers showed opposing trends, with increased angular velocity during Initial Flight and earlier initiation of deceleration, resulting in a reduction of angular velocity during the Opening Flight phase. The within-athlete standard deviation of *f*PC1 scores illustrated a difference between the two divers for within-athlete variability (Figure 13). The International diver was more likely to score negatively for *f*PC1, while the national diver was more widely scattered (i.e., positive and negative scores) (Figure 15). The International diver's scores indicated a more consistent movement structure across this aspect of the movement sequence.

The second *f*PC (*f*PC2) accounted for 15.8% of variation in the angular velocity data and was related to the formation of the Somersault Position and the Opening of the somersault position (Figure 16). Positive scoring dives had greater angular velocity during 10-50% of the movement sequence, with this reversing at 75% with a reduction in angular velocity. Negative scoring dives showed an opposing pattern. The International diver was again a strong negative scorer, while the National diver showed more variation and a trend towards being a positive scorer (Figure 13).

*f*PC3 accounted for 20% of variation in the angular velocity data and was related to the final adjustment in angular velocity before water on entry (Figure 17). Negative scoring dives were indicative of a higher angular velocity from 95% of the movement sequence until dive completion. *f*PC3 reported a substantial difference between the magnitude of within-athlete variability (Figure 13). The National diver showed a large dispersion with both positive and negative scores, while the International diver was also more likely to score positively (Figure 13 and Figure 17).

*f*PC4 reported the lowest level of variability for the angular velocity data (5.5%) and was associated with changes in angular velocity during the Somersault Flight (Figure 18). Positive scoring dives had greater angular velocity, while negative scores were associated with lower angular velocity during this phase. The International and National divers showed similar amounts of within-athlete variability in their *f*PC4 scores (Figure 13). Both divers showed positive and negative scores (Figure 18).

*f*PC5 represented 7.3% of the variability in the angular velocity data and was associated with angular velocity change in during the Initial and Opening Flight phases (Figure 19). Positive scores were indicative of greater angular velocity at takeoff (0% of the movement sequence), which was directly followed by a deceleration in the first 5% of the movement sequence. Positive scoring dives then accelerated again after 5%, with increased angular velocity continuing until 20% of the movement sequence. During 80-90% of the movement sequence positive scoring dives were again indicative of an increased angular velocity. Negative scorers showed relatively lower angular velocities across similar phases. For this *f*PC, the International diver showed a strong trend toward negative scoring, with the National diver showing more variation (Figure 13), being scattered across both positive and negative scores, (Figure 19).

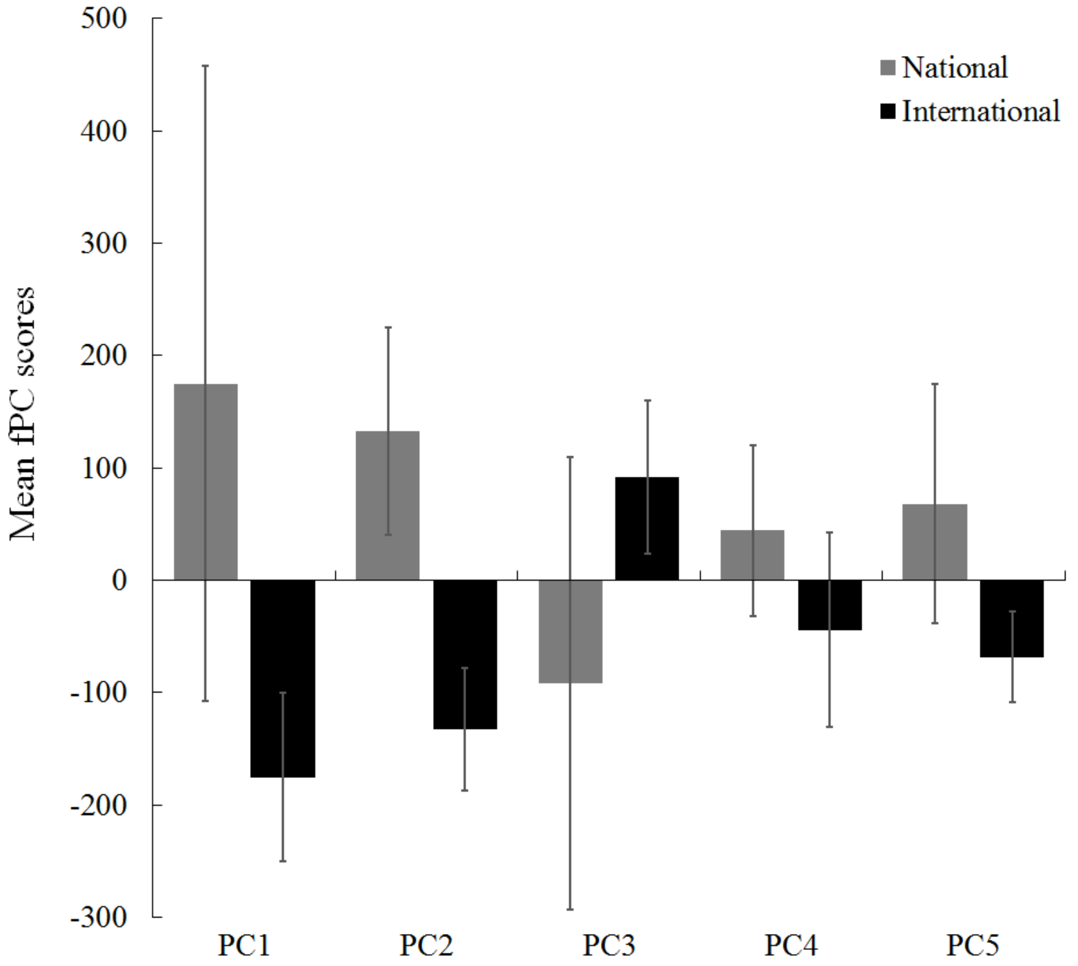


Figure 13. Structure (mean: column) and Magnitude (Standard deviation: error bars) of angular velocity curves variability: represented by the mean fPC scores and the standard deviation from the mean for the National and International divers

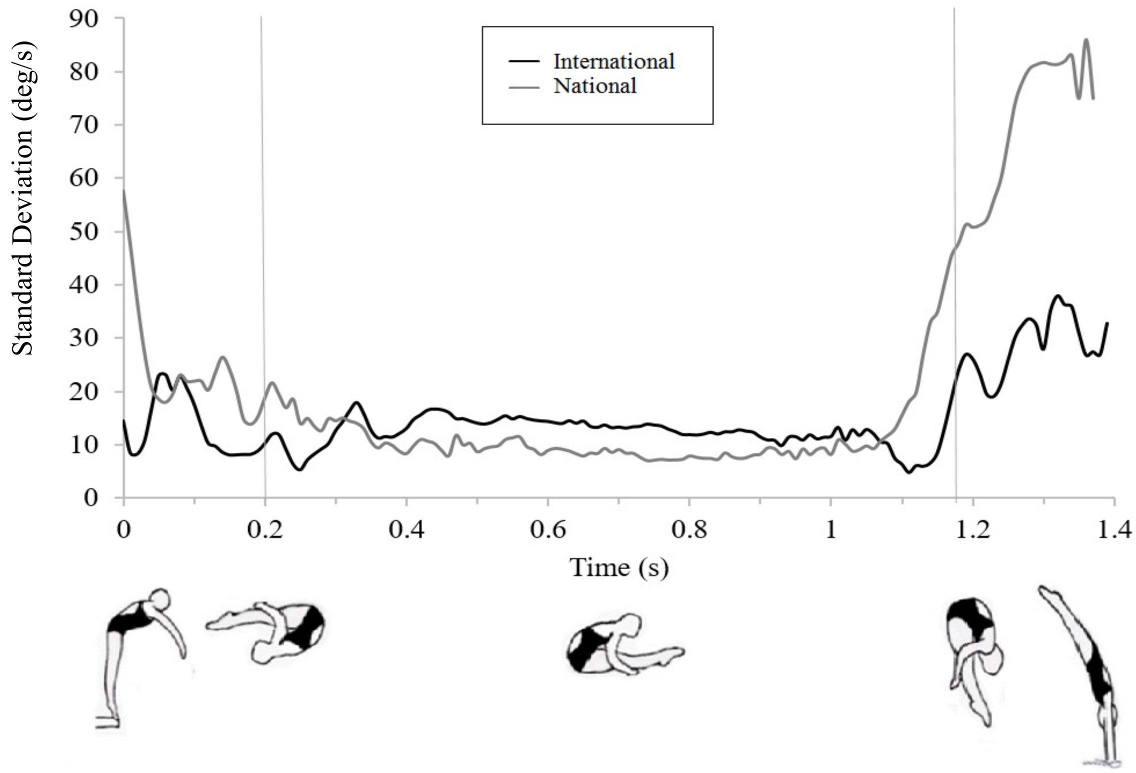


Figure 14. Standard deviation of the International and National divers' angular velocities time-series data measured at each time point

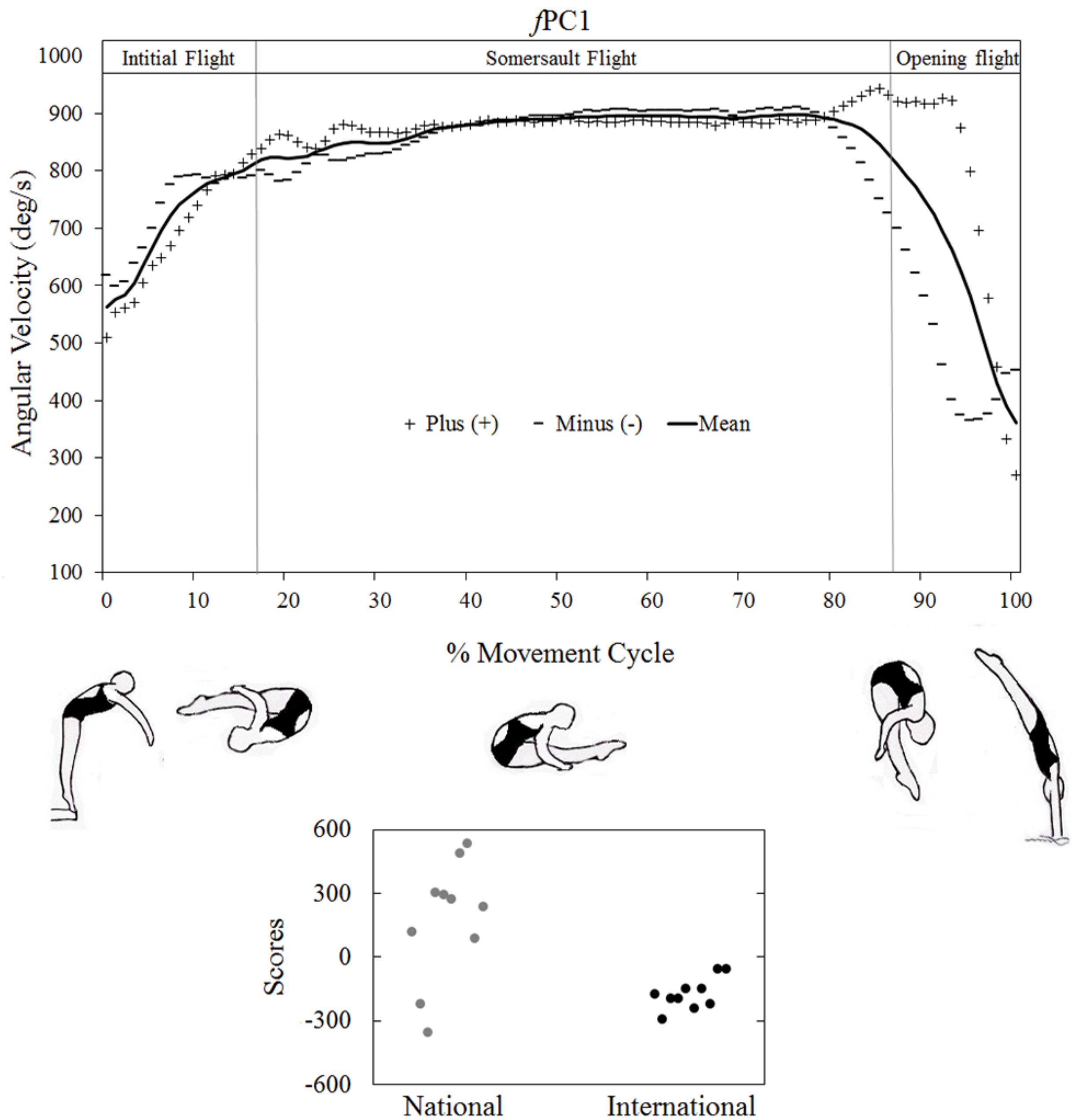


Figure 15. *f*PC1 for the Angular velocity time-series curve.
Figure notes: Solid line represents the mean, + represents the positive scoring dive performances and – represents the negative scoring dive performances.
The scatter plots represent the score spread for the National and International divers.

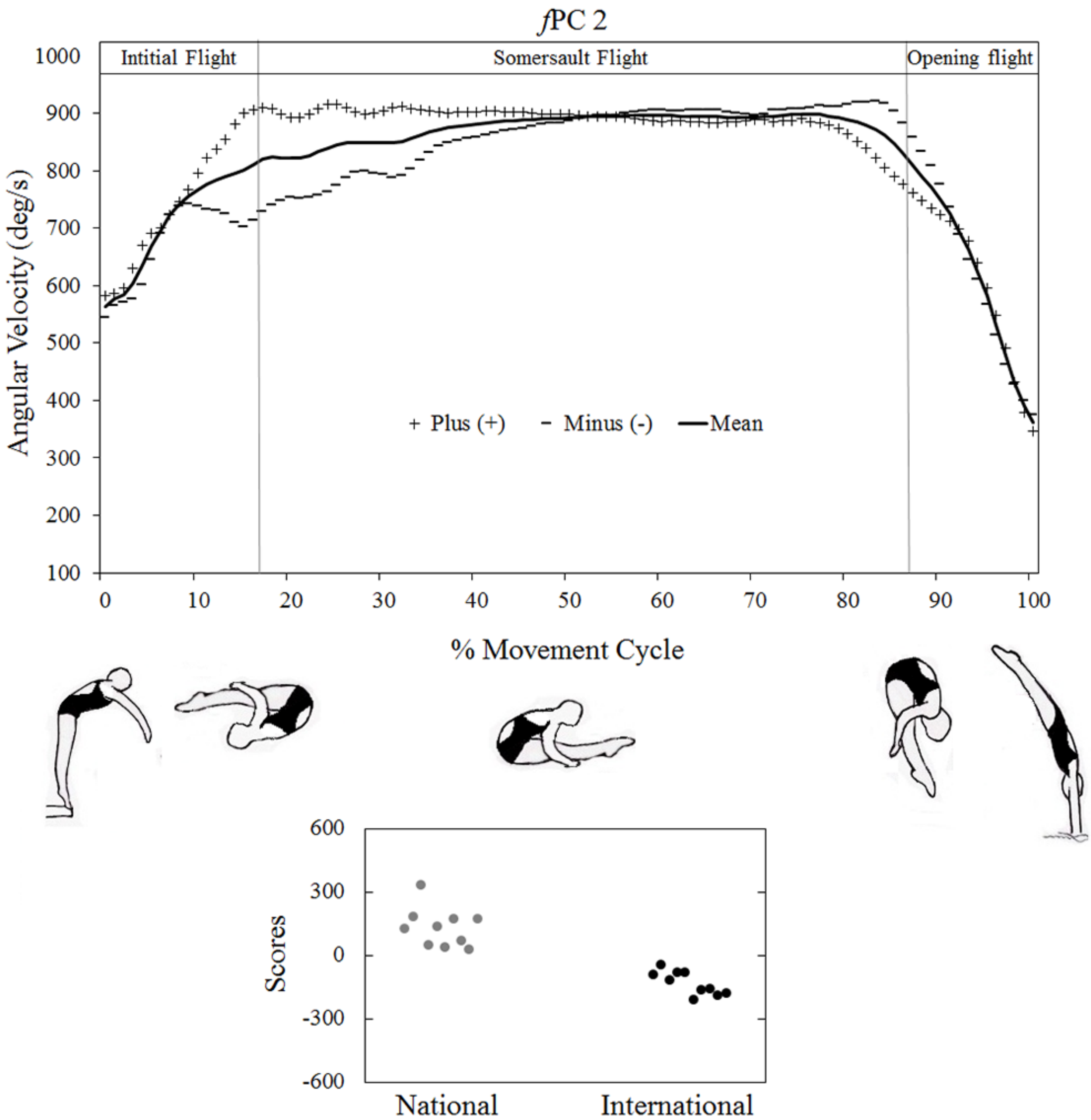


Figure 16. *f*PC2 for the Angular velocity time-series curve.
Figure notes: Solid line represents the mean, + represents the positive scoring dive performances and – represents the negative scoring dive performances.
The scatter plots represent the score spread for the National and International divers.

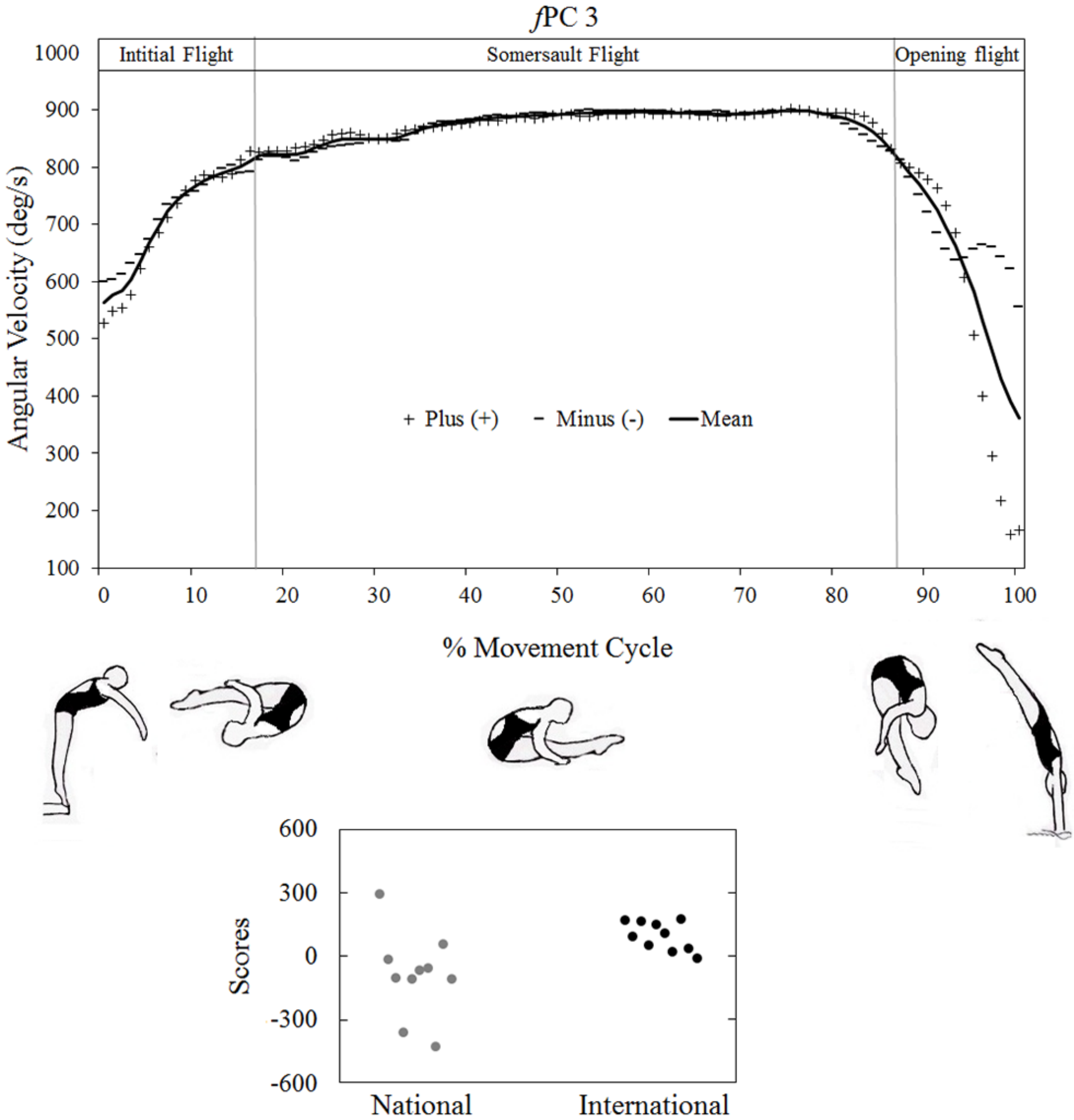


Figure 17. *f*PC3 for the Angular velocity time-series curve.

Figure notes: Solid line represents the mean, + represents the positive scoring dive performances and – represents the negative scoring dive performances.

The scatter plots represent the score spread for the National and International divers.

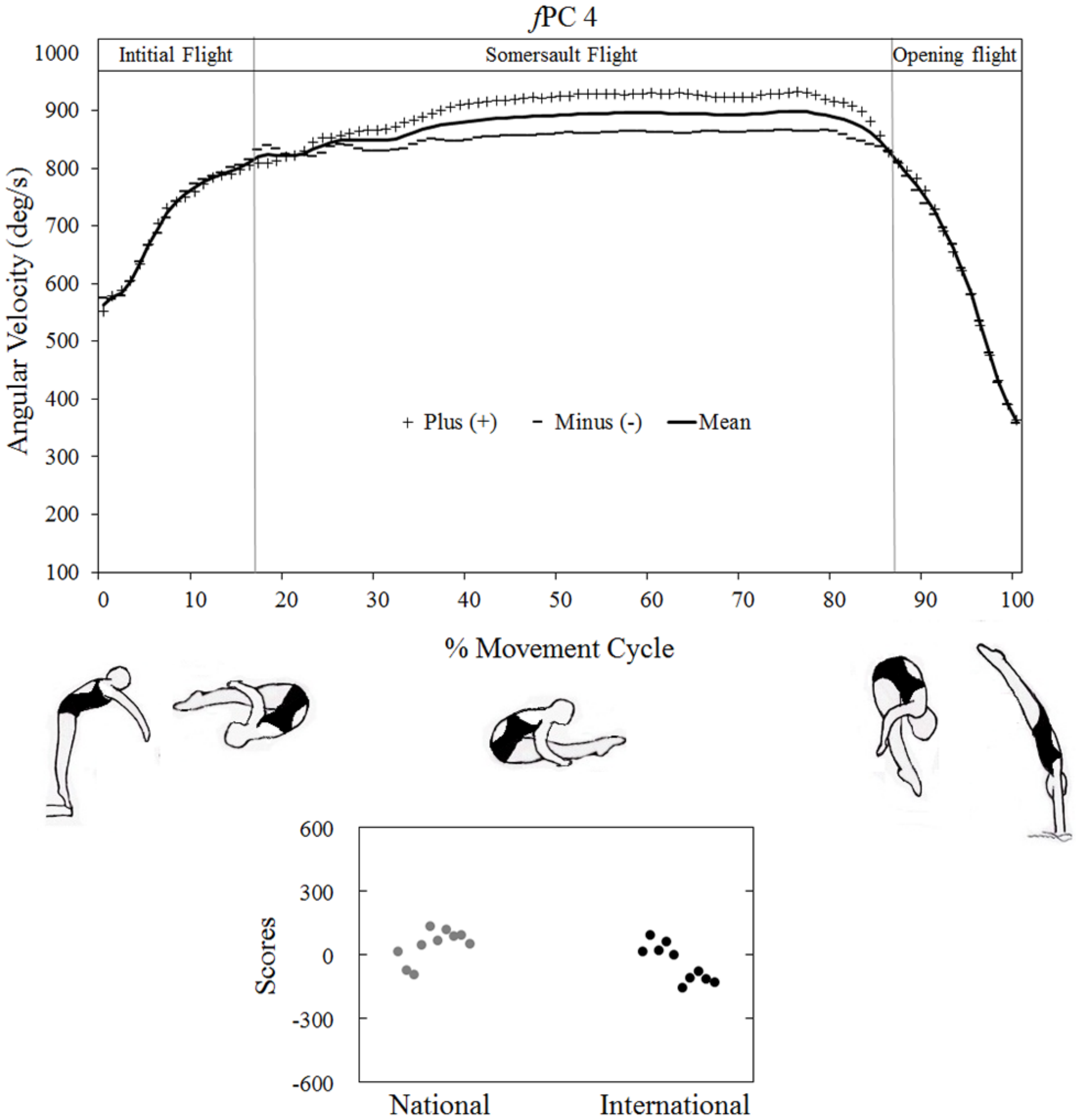


Figure 18. *f*PC4 for the Angular velocity time-series curve.
Figure notes: Solid line represents the mean, + represents the positive scoring dive performances and – represents the negative scoring dive performances.
The scatter plots represent the score spread for the National and International divers.

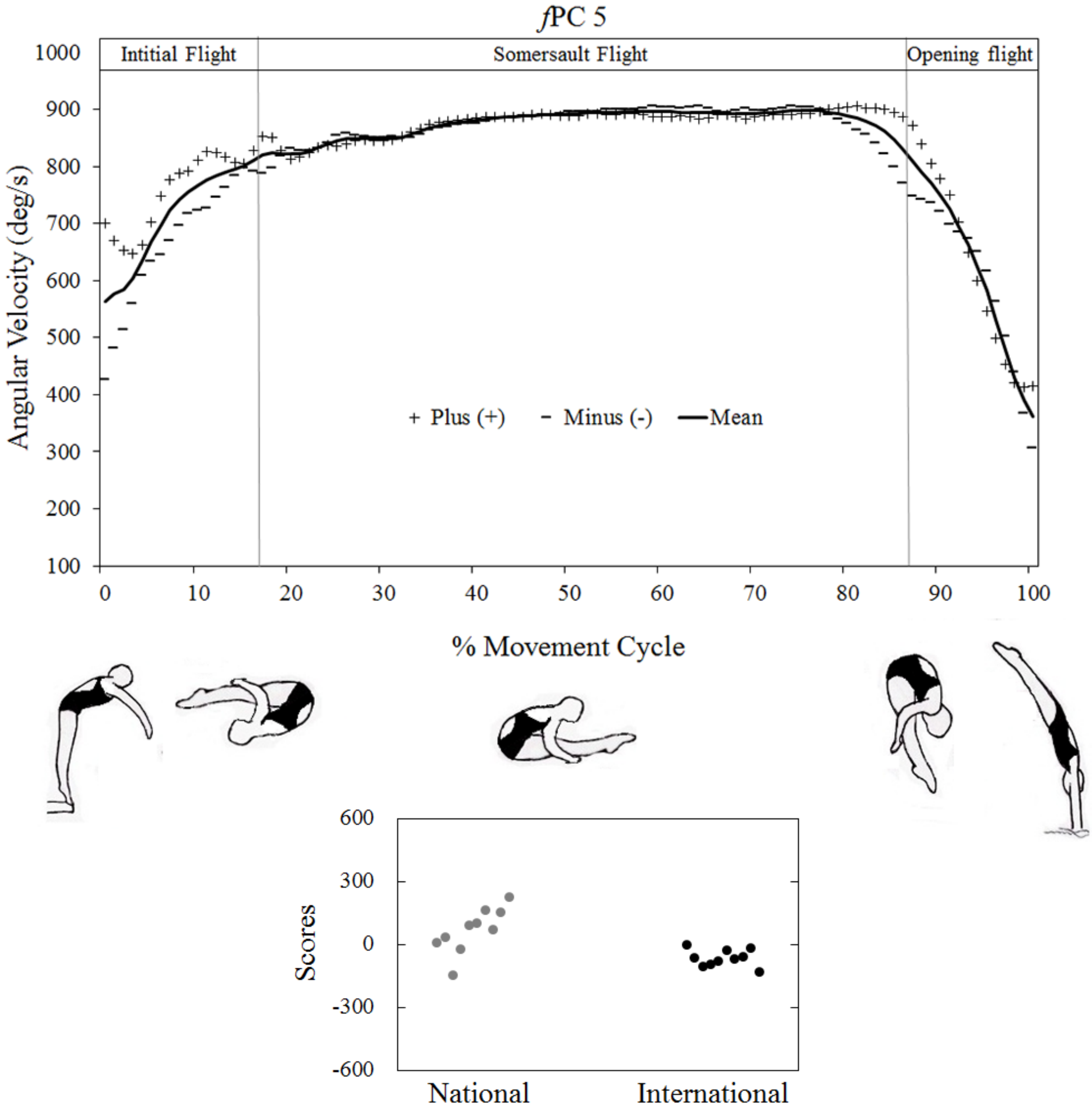


Figure 19. *f*PC5 for the Angular velocity time-series curve.
Figure notes: Solid line represents the mean, + represents the positive scoring dive performances and – represents the negative scoring dive performances. The scatter plots represent the score spread for the National and International divers.

Discussion

The primary purpose of this study was to evaluate the structure and magnitude of variability within 3½ pike somersault dives for two elite female springboard divers (National and International) using functional data analysis. The International level diver presented features that are indicative of a core pattern within their angular velocity curves with notable clusters of scores for the first, second, third and fifth *f*PCs. An overall core pattern was not as evident for the National level diver. To understand what this implies from a sports performance perspective we considered the International diver as a point of reference.

The first three *f*PC represented 84% of the total variation in the angular velocity data, and were consequently considered as the primary structures of performance variability in this data set. The International diver demonstrated a strong trend for negative scores on *f*PC1 (-175.2 ± 75.2) and *f*PC2 (-132.6 ± 55.0), and a strong trend for positive scores on *f*PC3 (91.9 ± 68.0). The key technical characteristics described by these three *f*PCs were a continual increase in angular velocity throughout the first 80-90% of the movement sequence, with an increased angular velocity prior to the commencement of angular deceleration. The conservation law of momentum states that angular momentum will remain constant when there is no external torques action upon an object. Therefore, once the diver has left the springboard the only manipulation to rotational mechanics is via increasing or decreasing the mass moment of inertia (Miller & Sprigings, 2001; Sanders & Gibson, 2000). Our International diver's structure of performance demonstrates a continual decrease in mass moment of inertia throughout the first 80-90% of the movement sequence. During the final 10-20% of the movement sequence the International diver was characterised by a more rapid deceleration. This alludes to the diver increasing her mass moment of inertia at a quicker rate, potentially achieving an extended body line earlier than the National diver, in preparation for the task constraint of a vertical entry angle (FINA, 2014).

Overall structure of the positive and negative curves represented a general stability within the angular velocity time-series during the plateau of the Somersault phase. *f*PC4 was specifically related to the angular velocity achieved during the Somersault phase and represented only 5.5% variability during the movement sequence, with both divers' scores being orientated either side of the mean line (Figure 18). The additional *f*PCs represented variability during the formation (Initial Flight) and deformation (Opening) of the somersault position.

The formation of the somersault is technically the most crucial aspect of the dive flight, as it will determine the length of time a diver can spend at their smallest mass moment of inertia and consequently highest rotational speeds. It can be theorised that the variability during the Opening phase was structured according to the gradient of the angular velocity slope during the Initial Flight. For example, where *f*PC1 demonstrated 48% of the explained movement variability, dives with greater angular velocity at the beginning of flight resulted in earlier initiation of angular deceleration (Figure 15). Previous studies in somersaulting biomechanics have termed this variation during the Opening phase as a functional adaptive strategy that allowed gymnasts to consistently land upright on ground contact (Bardy & Laurent, 1998; Gittoes et al., 2011; Lee et al., 1992). Prospective (visual) feedback strategies have been used by gymnasts to control their mass moment of inertia in relation to the time to ground contact (Bardy & Laurent, 1998). Similarly divers are able to achieve consistent total angular displacement prior to water entry for the highly complex 3½ pike somersault dive (Sinclair et al. (2014) and Chapter 4). Divers within the current study may be using visual cues and a learned sense of timing throughout the first two phases of the dive flight to spatially orientate themselves (O'Brien, 2003, pp. 94-95), and thus adapt their angular deceleration according to time to water contact.

As hypothesised, the magnitude of variability (or within athlete variability) was higher for the National diver across the *f*PCs when compared to the International diver. This was particularly true for *f*PC1 and *f*PC3. This may be associated with the national diver's reduced capacity to perform the highly complex aerial sequence. The forward 3½ pike somersault dive was a relatively new skill for the National level diver, with minimal competition experience. Thus, they may still be considered under the *coordination* phase of learning (Newell, 1985), where higher random variability may be occurring as they search for appropriate movement coordination patterns (Button et al., 2003; Wilson et al., 2008) to link the multiple phases of flight. The National divers largest spread of scores were related to *f*PC1 (SD = 282.6) and *f*PC3 (SD = 201.5), which demonstrate higher random variability during the Initial flight and Opening phases. It may be that the National diver was still learning to coordinate her springboard approach and takeoff to generate adequate linear and angular momentum for the dive flight of the 3½ pike somersault dive. Random fluctuations in the angular velocity during the Initial flight phase is most likely to be associated with the springboard approach mechanics. The stability within the Somersault phase may be where the National diver is searching for appropriate feedback information and strategies in order to adjust her angular deceleration during the Opening phase and achieve safe water entry.

Traditionally, expertise was associated with a decrease in movement variability (Bartlett et al., 2007) but under the dynamical systems theory, variability is often considered to increase with expertise (Wilson et al., 2008) and can be functional in adapting to perturbations during a movement sequence (Hamill et al., 1999). Opposing the dynamical systems model, our International diver reported less variability than the National diver in four out of the five *f*PC (Figure 13). The variability accounted for in *f*PC4 was the lowest across both skill levels (5.5%), however the International diver's standard deviation was slightly greater than that of the National diver. It may be that the International diver has been more proficiently trained at using a prospective feedback back strategy throughout the entire movement sequence from takeoff to water entry, allowing her the ability to functionally adapt and control her angular velocity throughout the entire movement sequence. The International diver's more repeatable structure of performance supports the theory that expert performers within the acrobatic sporting context are able to produce a consistent performance outcome, while under some level of functional control within the rotational mechanics (Bardy & Laurent, 1998; Gittoes et al., 2011; Yeadon & Hiley, 2014).

Interpretations from the limited subject size data presented may potentially reflect idiosyncratic (i.e., atypical) functional movement characteristics, structural variability and magnitudes of variability. Therefore, the findings should not be extrapolated to other divers of similar or different skill levels. Regardless, the use of a large sample size per individual and the novel analytical approach for continuous movement patterns of springboard divers provides additional methods for how to sport scientists and practitioners can identify the intricate and unique nature of divers to optimise technique, reduce performance error and improve overall skill.

Conclusion and Perspectives

The present study provides a new data analysis technique (*f*PCA) for assessing the entire movement sequence of not only springboard diving but other contexts of acrobatic sports. Somersault rotations are highly complex skills that require athletes to coordinate multiple degrees of freedom. While this study only takes into context one variable during the forward 3½ pike somersault dive (angular velocity), it is the first to use a holistic approach that does not require pre-determined discrete variables to compare the intra and inter athlete differences (For example see Hiley et al. (2013)). *f*PCA considers the entire movement sequence without discarding any information, providing a quantitative waveform analysis. The present data showcased the potential of *f*PCA to determine an individual springboard diver's skill level, with the Internationally ranked diver presenting less random variability and greater functional control in response to feedback from the initiation of the somersault position. To further explore and monitor the effect of variability within angular velocity curves, correlations between *f*PC scores and key discrete performance outcome variables may be useful to better understand how to improve coordination, control, skill and therefore performance.

References for this chapter are included in the list of references at the end of this thesis

CHAPTER 6

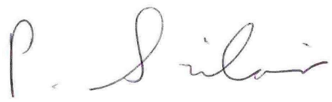
A continuous times-series and discrete measure analysis of individual divers performing the 3½ pike somersault dive

The following chapter is formatted for submission to *Scandinavian Journal of Medicine & Science in Sports.*

Author contribution statement

As a co-author on the paper presented within this chapter entitled "*A continuous times-series and discrete measure analysis of individual divers performing the 3½ pike somersault dive*", as well as being Primary Supervisor throughout the Doctor of Philosophy candidature of Cherie Walker, I confirm Cherie's contribution to the paper as follows:

- Conception and design of the research
- Data collection
- Analysis of data and interpretation of the findings
- Writing the paper and critically appraising content within the manuscript

Signed:  Date: 11/08/16

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Faculty of Health Sciences

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A continuous times-series and discrete measure analysis of individual divers performing the 3½ pike somersault dive

By

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Abstract

Springboard diving training is focused on the repetition of a skill in order to create movement accuracy, stability and consistency. Individuals may create these task demands under different modalities. Within-participant study designs provide the ability to understand these modalities. To understand the unique nature of springboard divers performing the forward 3½ pike somersault dive, separate *f*PCA were performed on repeated measures of two individual (International and National) divers' angular velocity curves. The first five *f*PC represented 98.2% variability in the International diver's angular velocity curves and 98.5% for the National diver. To determine the implication of angular velocity variability, *f*PC scores were correlated to discrete performance kinematics (maximum depression, takeoff posture, dive height, dive distance, angular displacement, time of flight and entry posture). Individual divers presented with their own unique type and number of significant correlations (International = 4; National = 11). Only one common significant correlation was evident for both divers; higher angular velocity during the Initial Flight and/or Somersault phases resulted in more vertically aligned entry posture (International: *f*PC1 $r = -0.761$, $p < 0.05$; National: *f*PC3 $r = -0.796$, $p < 0.01$). These findings highlighted individualised difference in areas of performance abilities and susceptibilities, which can be used by coaches to improve the success of the forward 3½ pike somersault dive.

Key words: Functional principal component analysis, kinematics, biomechanics, acrobatics, springboard diving

A continuous times-series and discrete measure analysis of individual divers performing the forward 3½ pike somersault dive

Introduction

In the context of springboard diving, coaches and sport scientists are continually focused on individual performance optimisation; often aiming to create movement accuracy, stability and consistency (Bardy & Laurent, 1998; Gittoes et al., 2011) whilst also attaining maximal height at dive takeoff, necessary rotational velocities during dives, and a vertical aligned posture on water entry. Varying functional control strategies that permit flexibility and adaptability within the movement pattern of dives are likely required to consistently achieve these performance outcomes (Bardy & Laurent, 1998; Barris et al., 2014; Wilson et al., 2008). Such movement adaptability must be controlled and coordinated as multiple phases within a complex movement pattern are linked together to produce 'homogeneity, integration and structural unity' (Bernstein, 1967, p. 30) to create a complete skill execution (Newell, 1986).

While previous studies provide valuable insight as to the biomechanical and technical requirements of high degree of difficulty dives (for example see Sanders and Gibson (2000)), existing methodological approaches have traditionally relied on group study designs where normative (mean) values are identified to provide benchmarks for training optimisation (Brisson & Alain, 1996; Schöllhorn & Hans, 1998) and common performance characteristics of highly skilled divers. However, these approaches generalise across individuals and fail to consider how an individual diver may idiosyncratically perform the dive. Group study designs also prevent researchers from understanding exactly when and how divers are functionally attempting to explore, control and adapt movement across dive phases to achieve a desired posture at water entry (Bartlett et al., 2007). From this standpoint, group forms of analysis may potentially conceal more finitely informative data related to the individual characteristics (Ball

& Best, 2012) (or signatures) of movement, and limit the capability of practitioners to objectively identify and optimise the preferred features of movement.

Within-participant research design are becoming more common in the sports sciences and within performance analysis (Barris et al., 2014; Schöllhorn & Hans, 1998). These designs are particularly pertinent when considering that the same performance outcome can be produced under variable motor patterns, with the same skill by two individuals or even two attempts by the same individual being achieved under different coordination and control patterns (Bartlett et al., 2007; Brisson & Alain, 1996; Glazier et al., 2003; Newell & Slifkin, 1998). Within-participant approaches therefore provide the ability to focus and examine individual's common movement pattern structure, variability from this structure and uniqueness during repeated trials on a given task. These designs help researchers and practitioners better understand how movement technique is developed, coordinated and adapted. The main challenge then, is how to sensitively detect and analyse these movement features.

Functional principal component analysis (*f*PCA) presents an opportunity to detect and understand how an individual's movement sequence is structured (Dona et al., 2009). *f*PCA considers the entire series of data as a single functional entity (Harrision, 2014), where principal components describe the structure and shape change of curves from repeated measures of a movement sequence (Ryan et al., 2006). Currently, *f*PCA has been used to biomechanically analyse structural differences and variability within continuous time-series data from multiple sporting contexts including; rowing (Warmenhoven et al., 2015), swimming (Sacilotto et al., 2015), weight lifting (Kipp & Harris, 2015), as well as gait kinematics (Daffertshofer et al., 2004; Dona et al., 2009; Donoghue et al., 2008; Ryan et al., 2006).

Previous research, analysing the continuous characteristics of angular velocity from performances of the forward 3½ pike somersault dive have identified technical differences between skill levels using *f*PCA (Chapter 5). Repeated measures from two skill levels were combined into a single analysis and technical differences were differentiated via the magnitude of deviation for each individual. Higher skill was associated with increased consistency within angular velocity structure of performance, while lower skill presented larger magnitudes of variability. Combining the movement sequences of divers performing the forward 3½ somersault into a single analysis, however, may have reduced and/or suppressed key features within the participants' individual angular velocity curves and thus limited the ability of researchers to completely understand an individual's unique nature and technical capabilities.

Using the application of functional data analysis (FDA) and customary discrete analysis procedures (two-dimensional video footage), the purpose of this paper was to separately examine the repetitive technical movement characteristics of two individual highly skilled springboard divers performing the forward 3½ pike somersault dive. The study approach and design sought to determine for each diver: (1) the within-athlete angular velocity movement pattern structure (i.e. shape changes within an athlete's time-series variables); (2) the magnitude of variability across particular phases of a dive movement sequence (Dona et al., 2009), and (3) how discrete performance variables (typically measured in past springboard diving research) correlated with the individual's structure and magnitude of variability in angular velocity time-series data. It was hypothesised that the mean shape changes of angular velocity increase, plateau and decrease would be similar for the two athletes. By contrast, it was hypothesised that the magnitude of variability would present different patterns of deviations and consequently unique patterns of significant correlations with performance variables for each individual diver (in response to our previous findings reporting individual differences in the magnitude of variability in angular velocity curves, Chapter 5). Overall, we proposed that the combined analysis procedures applied could generate valuable implications when evaluating individual's movement technique and ability to produce a successful skill.

Methods

Participants

Following institution ethical approval and consent, participants were two highly skilled female springboard divers. Participant 1 (age - 22years; height - 1.67m; mass - 58.3kg) was a FINA internationally ranked diver (termed: International). Participant 2 (age - 16 years; height - 1.57m; mass - 53.8kg) was a nationally ranked junior elite diver (termed: National). Both divers were completing intensive training at the time of data collection, were injury free, and were adhering to a minimum of ten training sessions per week.

Procedures and Experimental Set-Up

Wireless Inertial Measurement Units (IMUs; IMeasureU®, Auckland, New Zealand), with a sample frequency of 100Hz, were used to obtain angular velocity data during full completion of forward 3½ pike somersault dives. Prior accuracy assessment between the IMUs' gyroscope output measures and three-dimensional motion analysis capture (Cortex 3.3 Motion Analysis Corporation, USA) reported a mean percentage difference of 0.5% and <1.0% difference when integrating the angular velocity signal to obtain change in angular displacement, providing validity to IMU gyroscope measures (Walker et al. (2015) and Chapter 3). IMU units were small (22 mm x 34 mm x 10 mm), lightweight (12g) and non-distracting to divers (Finch et al., 2011). Secondary to the IMUs, a high-speed Casio Exilim EX-FH100 camera was placed level and perpendicular to the chosen 3m springboard. The camera was set to a 120Hz frame rate, and a shutter speed of 1/250s, with a field of view limited to dive approach, dive flight and water entry.

Data were collected across three regular sessions for each diver, with an aim to collect multiple repeated trials of the 3½ pike somersault dive. These sessions were in line with the divers regular training and therefore did not interrupt the training routine, i.e. heavy weight sessions were not conducted the morning of the 3m springboard sessions, reducing the potential for muscle fatigue and soreness. Divers (with coaches present) were instructed to perform their regular dry land warm up and aquatic training routine. Following warm up, two IMUs were adhered bilaterally to the posterior superior iliac spine (PSIS) with adhesive double-sided tape and secured with adhesive film (OpSite™ Flexigrid) to minimise IMU relative motion with respect to the PSIS skin artefacts (Forner-Cordero et al., 2008). Two IMUs were applied as precaution in case one became dislodged during training. Neither became dislodged and the signal outputs were in agreement. Dynamic sports tape (Rocktape) was also applied to clearly identify the lateral malleolus of the fibula, middle iliac crest and greater tubercle of the humerus on video footage. Before commencing dives, participants were instructed to stand stably on the springboard for 2-3s, followed by a tap to the IMUs prior to initiating a dive approach. The tap created a clear spike in the gyroscope data and was visible on the video footage, allowing synchronisation between both systems. Each performance of the 3½ pike somersault dive within the sessions was filmed and had IMU data recorded.

Data Analysis

In total, ten trials of the 3½ pike somersault dive were collected and analysed for each participant. A custom made Matlab script (The MathWorks, Inc., Natick, MA, USA) extracted gyroscope data relevant to the somersault axis and was examined in Excel (Microsoft Corp, Redmond, Washington, USA). Time zero was set as the takeoff (i.e., the last frame the divers' feet were on the springboard) for each trial. Takeoff events were identified via synchronisation between IMUs and video footage. However, in some cases where a tap to the IMU was not performed before (i.e., the diver forgot), angular velocity plots were visually overlayed to match the takeoff event pattern. Pilot testing with trials that did contain the synchronisation signal revealed that the visual alignment process had a maximum mean error of 0.02s, with a mean of 0.01s for takeoff identification.

Initial data processing

A linear length normalisation strategy using an interpolating cubic spline was applied to normalise each diver's ten angular velocity curves to express 100% cycle of the dive movement pattern (Helwig et al., 2011). The normalisation did not have a large impact on the linear compression or expansion of the raw data as the standard deviation for the total time of flight was minimal; 1.39±0.01s (International) and 1.36±0.03s (National). Once normalised, each athlete's 100% dive cycle was divided into three flight phases: Initial Flight, Somersault and Opening (Table 12). Flight phases were identified through the video footage and were time synchronised with the angular velocity time-series data.

Table 12. Definition of the dive flight phases.

Dive flight phase	**Definition**
Total flight	Defined from final frame of foot contact with the springboard, takeoff, to the first frame where hands broke the water on entry (Sanders & Gibson, 2000).
Initial flight	Defined from takeoff to the first frame where the diver's hands touched their legs to form the somersault position
Somersault	Defined from the formation of the somersault position to the first frame where the diver's hands left their legs.
Opening	Defined from the opening of the somersault position to the first frame where the diver's hands break the water.

Time series functional principal component analysis

A custom made functional data analysis Matlab script (The MathWorks, Inc., Natick, MA, USA) was generated in accordance with available software from a functional data analysis website (http://www.psych.mcgill.ca/misc/fda/). In this script, b-spline basis functions were used for the creation of angular velocity time-series curves. The smoothing parameter was selected using a combination of a generalised cross validation procedure (Ramsay & Dalzell,

1991) and visual inspection. From these smoothed curves, the functional principal components (*f*PCs) were derived for each individual diver's angular velocity-curves. Each diver's *f*PCs were varimax rotated to allow for an informative evaluation of specified parts of the angular velocity-time curves (Ramsay & Silverman, 2013). Separate weighting of the angular velocity-curves were conducted for each individual diver's dataset from their first five *f*PCs. The resulting scalars were referred to as *f*PC scores. Individual *f*PC scores were calculated by multiplying each data function by the relevant *f*PC and integrating over (0,1) (Donoghue et al., 2008). The occurrence and magnitude of angular velocity variability was graphically represented as individual *f*PC plots, illustrating the mean curve of each diver's angular velocity and two additional curves created by adding (+) or subtracting (-) a multiple of the *f*PC (Dona et al., 2009). Descriptive statistics represented the percentage of variability within each principal component (Dona et al., 2009).

Discrete (Kinematic Variable) Analysis

Key discrete kinematic performance variables (see Table 13 for a list and their definitions), identified from past springboard diving research (e.g., Sanders and Gibson (2000)), were extracted from video footage via two-dimensional digitisation of the anatomical land marks using Tracker software (Brown, 2008). The *x* and *y* pixel coordinates were converted to real world measures via two-dimensional DLT parameters (Reinschmidt & Bogert, 1997). This was based on a calibration frame scaled according to the position of the 3m springboard and coordinate calculation equations (Walton, 1981), (Appendix 4). In addition to the kinematic variables collected via video footage, trapezoidal integration of IMU angular velocity times-series data were used to calculated the total change in angular displacement of individual dive performances (i.e., the amount of rotation achieved).

Shapiro-Wilk test of normality was conducted for each individual diver's discrete kinematic variables and *f*PC scores. For normally distributed variables ($p > 0.05$), Pearson's product-moment correlations were used to assess the relationship between each athlete's angular velocity time-series *f*PC scores and performance measures. For non-normally distributed variables Spearman's rank-order correlations were used to assess these relationships (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY, USA: IBM Corp). These correlations examined relationships between pre-flight kinematics (e.g., maximum depression and takeoff posture) on the magnitude and occurrence of angular velocity variability, as well as the effect of these variations during the dive flight (dive height) and post flight (Total angular displacement, total flight duration, entry posture and dive distance). Statistical significance was set to $p < 0.05$.

Table 13. Definition of discrete performance measures used in prior studies.

Performance measure	**Definition**
Max. depression (m)	Maximum downward vertical distance the tip of the springboard travelled
Takeoff body alignment (°)	Defined from the line between the lateral malleolus and greater tubercle of the humerus with respect to the right hand horizontal at the final frame where the feet were in contact with the springboard (takeoff) (Sanders & Gibson, 2000)
Takeoff hip angle (°)	Relative angle between the lower limb and trunk segment at takeoff
Entry body alignment (°)	Defined from the line between the lateral malleolus and greater tubercle of the humerus with respect to the right hand horizontal at the first frame the hands broke the water (Sanders & Gibson, 2000)
Entry hip angle (°)	Relative angle between the lower limb and trunk segment at the first frame the hands broke the water
Total Flight duration (s)	Duration from the takeoff to hand entry
Total Flight angular displacement (°)	Total rotation achieved from takeoff to hand entry
Dive height (m)	Peak height of the diver's iliac crest. Calculated as the vertical difference between the iliac crest at peak height and the iliac crest at takeoff
Dive distance (m)	The horizontal distance travelled by the diver with respect to the end of the springboard. Calculated as the linear difference between the iliac crest at hand entry and the iliac crest at takeoff

Results

International diver

The first five *f*PC's represented 98.2% of the variation in the International diver's angular velocity curves. *f*PC1 accounted for 35% of this variability and was associated with angular velocity achieved during the Somersault phase (Figure 20 - 1A). Dive performances of the 3½ pike somersault with positive scores reflected higher rotational speeds. *f*PC1 positive scores were correlated with greater total flight angular displacement (r = 0.870, p = 0.001), greater vertical body alignment (closer to 90°) (r = -0.761, p = 0.011) and a more extend hip (r_s = 0.685, p = 0.029) upon water entry (Table 14).

Functional principal components two and three each accounted for 19% and 24% of the variability in the angular velocity curves. Both *f*PC2 and *f*PC3 were associated with final adjustments of angular velocity prior to water entry in response to small deviations during the first two phases of the dive flight (Figure 20 - 1B and 1C). *f*PC2 represented a small deviation from the mean at 25-35% of the movement sequence, with greater rotational speeds during this portion of the movement sequence (negative scores) reflecting a more rapid angular deceleration during the final 5% of the movement sequence. *f*PC2 correlated to entry body alignment with negative scoring dives achieving a more vertical body alignment (r = 0.664, p = 0.036) (Table 14). Similarly, *f*PC3 had a small deviation from the mean, but during the Initial flight (7-15% of the movement sequence), with greater rotational speeds (negative scores) resulting in an earlier and more rapid angular declaration during the final 10% of the movement sequence. Greater maximum depression of the springboard during the dive takeoff negatively correlated to *f*PC3 (r_s = -0.709, p = 0.022).

*f*PC4 was associated the angular velocity achieved during the Initial flight and accounted for the least variability (10%) in angular velocity curves for the International diver. Positive scoring dives rotated faster during the first 10% of the movement sequence, while negative scoring dives rotated slower (Figure 20 - 1D). *f*PC4 positive scoring dives were associated with less dive height ($r = -0.693$, $p = 0.026$) (Table 14).

The final *f*PC represented 11% of variability in the International diver's angular velocity curves. *f*PC5 reflected variability associated with the timing of the commencement of angular deceleration. Negative scoring dives began to decelerate at 80% of the movement sequence, whilst positive scoring dives began to decelerate toward 85% (Figure 20 - 1E). No significant correlations were found between *f*PC5 and performance measures ($p > 0.05$) (Table 14).

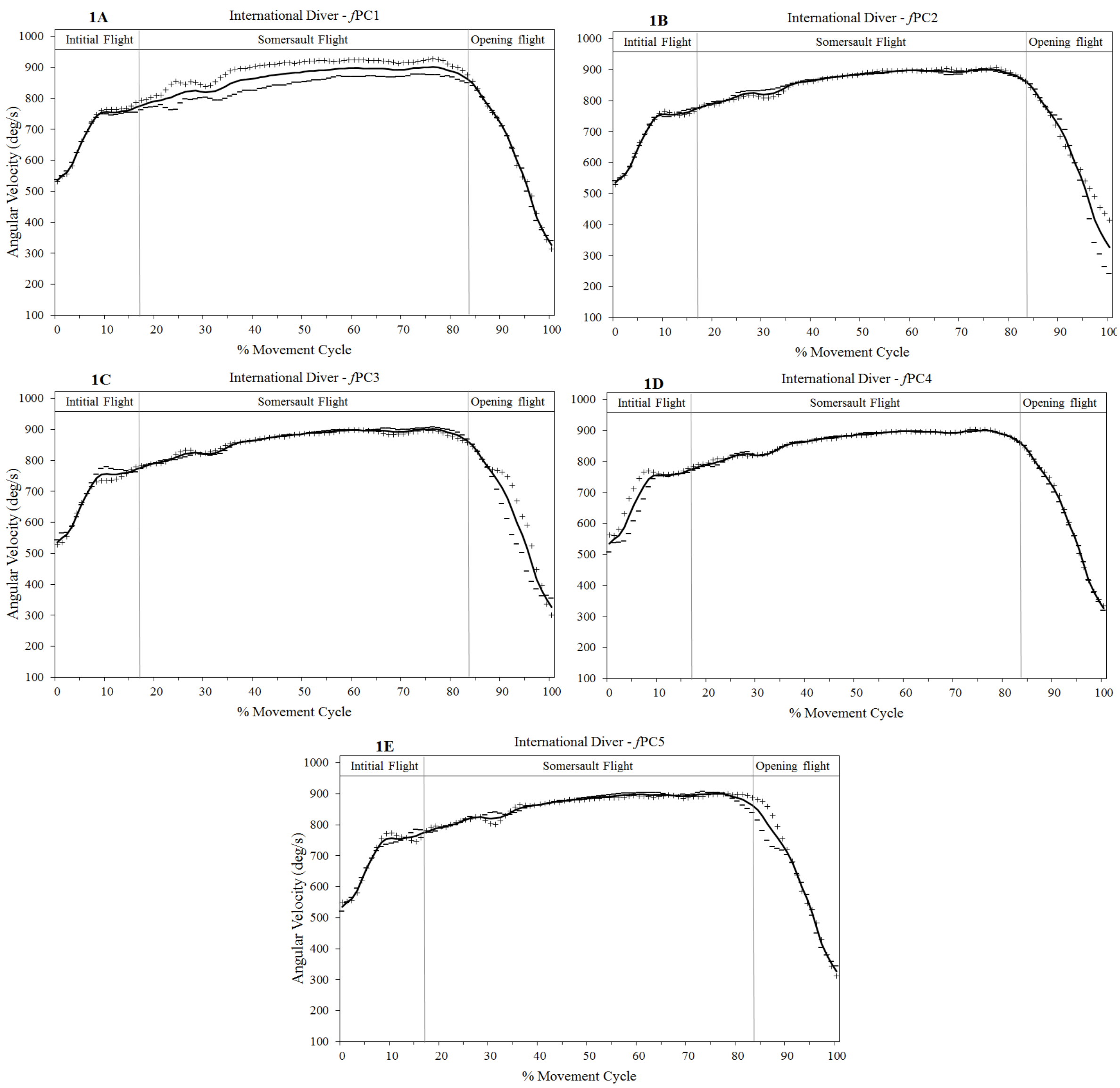


Figure 20. Angular velocity time-series *f*PC for the International diver's forward 3½ pike somersault dives.
Figure notes: Solid line represents the mean, '+' represents the positive scoring dive performances and '-' represents the negative scoring dive performances.

Table 14. International diver's correlation between performance measures and angular velocity time-series fPC scores during 3½ pike somersault dives.

Performance Measure	***f*PC1**	***f*PC2**	***f*PC3**	***f*PC4**	***f*PC5**
Maximum depression	0.38	-0.25	-0.71*	-0.30	-0.21
Takeoff body alignment	0.12	-0.60	-0.21	-0.50	-0.16
Takeoff hip angle	-0.16	0.16	0.07	-0.09	-0.17
Dive height	0.06	-0.22	-0.52	-0.69*	-0.37
Dive Distance	-0.53	0.22	-0.34	-0.14	0.44
Total Flight duration	-0.20	-0.53	-0.11	-0.45	0.18
Total Flight Displacement	*0.87***	-0.58	-0.21	0.08	-0.58
Entry hip angle	*0.69**	-0.39	-0.49	0.20	-0.515
Entry body alignment	*-0.76**	*0.66**	0.37	-0.15	0.39

Table Notes: * $p = < 0.05$, ** $p = < 0.01$

National Diver

The separate *f*PCA of the National diver's 3½ pike somersault dives, revealed that the first five *f*PC represented 98.5% of the variation in her angular velocity curves. *f*PC1 accounted for 21% of this variability. In this case, positive and negative scoring dive attempts reflected the angular velocity achieved during 12-35% of the movement sequence. Positive scoring dives began with less rotational velocity, followed by a gradual increase in angular velocity during the remaining portion of the Somersault phase and later angular deceleration (85% of the movement sequence) (Figure 21 - 2A). The opposite trend was seen for the negative scoring dives with greater angular velocity, followed by a gradual decrease and earlier angular deceleration (75% of the movement sequence). *f*PC1 positive scoring dives were associated with greater dive distances ($r_s = 0.768$, $p = 0.009$) (Table 15).

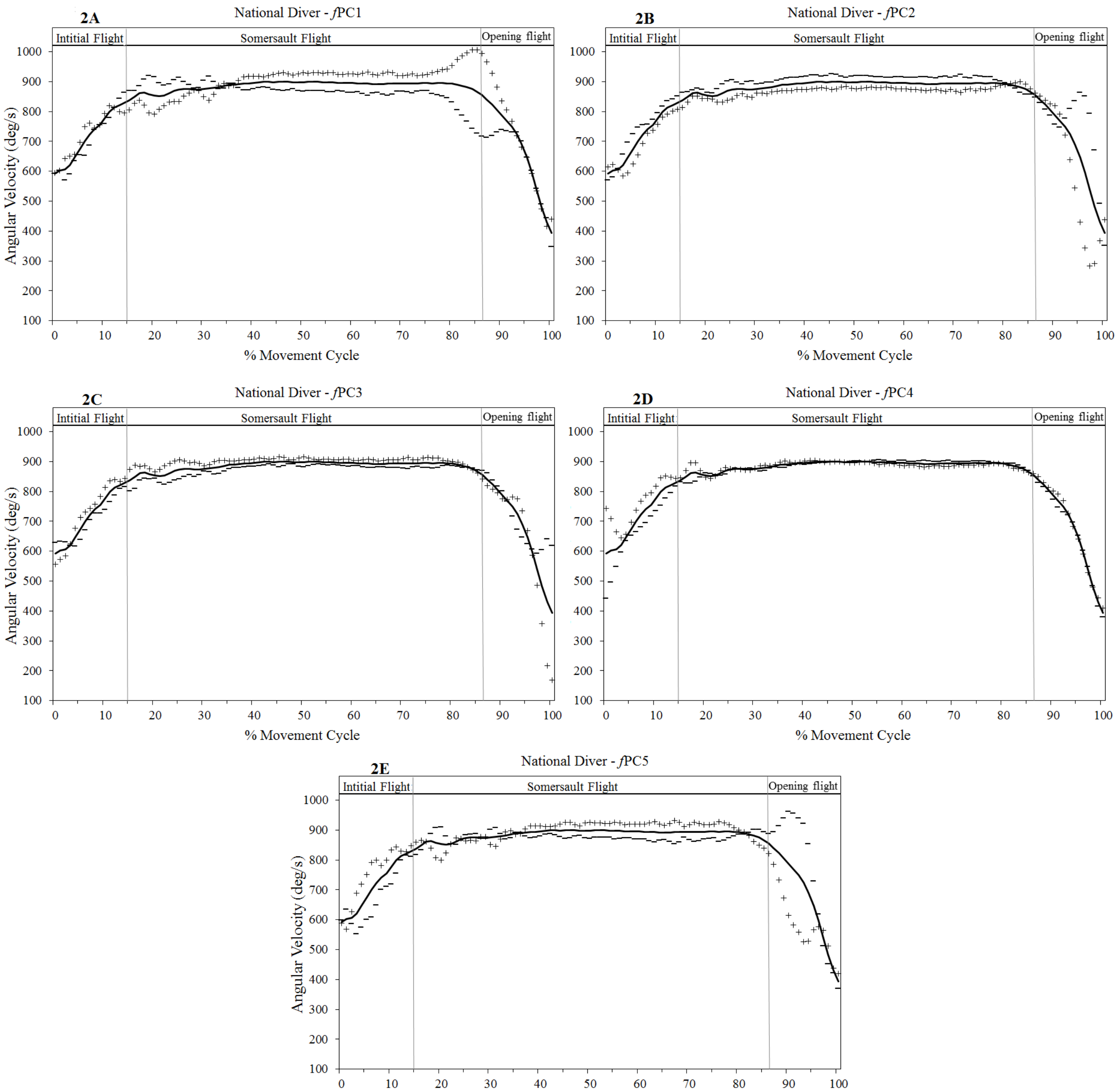


Figure 21. Angular velocity time-series ƒPC for the National diver's forward 3½ pike somersault dives.

Figure notes: Solid line represents the mean, '+' represents the positive scoring dive performances and '-' represents the negative scoring dive performances.

Table 15. National diver's Correlation between performance measures and angular velocity time-series fPC scores during the 3½ pike somersault dives.

Performance Measure	***f*PC1**	***f*PC2**	***f*PC3**	***f*PC4**	***f*PC5**
Maximum depression	-0.29	0.52	*0.72**	0.04	0.17
Takeoff body alignment	-0.09	0.30	-0.19	-0.50	0.34
Takeoff hip angle	0.26	0.01	-0.36	-0.41	-0.09
Dive height	*-0.38*	*0.75**	0.42	-0.39	0.62
Dive Distance	*0.87***	-0.26	0.24	0.52	*-0.68**
Total Flight duration	*-0.50*	*0.67**	0.03	-0.61	*0.53*
Total Flight Displacement	-0.33	-0.14	0.34	-0.03	-0.19
Entry hip angle	-0.52	*0.66**	*0.71**	-0.12	0.50
Entry body alignment	0.14	-0.43	*-0.80***	-0.15	-0.24

Table Notes: * p = < 0.05, ** p = < 0.01

The second *f*PC accounted for the highest variability within the National diver's angular velocity curves (30%) and was associated with an adaptation to lower (positive scores) or higher (negative scores) angular velocity during the first 80% of the dive movement sequence. Positive scoring dive attempts were associated with a rotational pause in the first 5% of the movement cycle, less angular velocity during the Somersault phase and a later initiation of angular deceleration (Figure 21 - 2B), whereas the reverse occurred for negative scoring dive attempts. Positive scoring dives were correlated to a greater dive height (r = 0.754, p = 0.012), longer dive duration (r_s = 0.665, p = 0.036) and more extended hip on water entry (r = 0.662, p = 0.037) (Table 15).

*f*PC3 reflected 13% of the variability in the angular velocity curves, and was associated with angular velocity across the movement sequence. Positive scores were associated with increased angular velocity throughout the dive, which was subsequently followed by a more rapid angular deceleration (Figure 21 - 2C). Positive scoring dives were correlated to greater maximum springboard depression (r = 0.720, p = 0.019), a more vertical body alignment (r = -0.796, p = 0.006) and more extended hip (r = 0.708, p = 0.022) on water entry (Table 15).

*f*PC4 accounted for the least variability (5%) during the angular velocity curves, but was associated with angular velocity achieved during initial flight. Positive scoring dives had greater angular velocity measures at takeoff (0%), which was directly followed by deceleration in the first 5% of the movement sequence. Positive scoring dives then accelerated from 5-20% of the dive movement sequence (Figure 21 - 2D). No correlations between the National diver's *f*PC4 and performance measures were apparent ($p > 0.05$) (Table 15).

The fifth *f*PC represented 30% of the variability in the National diver's angular velocity curves (largest alongside *f*PC2). Deviations from the mean were present across the entire dive movement sequence, with the greatest deviations occurring during the Opening phase (Figure 21 - 2E). Positive scoring dives, overall, had greater rotational speeds than negative scoring dives during the first two phases of dive flight. This was then associated with earlier initiations of angular deceleration at approximately 82% of the movement sequence. Negative scoring dives maintained and even increased their rotation speeds at 80% of the dive sequence, then began angular deceleration at approximately 92%. *f*PC5 positive scoring dives were correlated with less dive distance ($r = -0.675$, $p = 0.032$) (Table 15), though no other correlations were apparent.

Discussion

The primary purpose of this study was to assess repeated performances of the forward 3½ pike somersault dive of individual female athletes. A within-participant study design was selected to demonstrate the unique nature of individual divers and how they coordinate their movement sequence to perform the 3½ pike somersaults. The combination of applying functional principal component analysis (*f*PCA) to angular velocity time-series data and correlating these findings with discrete kinematics measures demonstrated the unique differences between two highly skilled divers within this study.

Angular velocity curve structure

It was hypothesised that the structure of each diver's mean angular velocity curve would have a similar shape. Both divers presented clear angular acceleration, and deceleration. However, the angular velocity plateau during the Somersault phase was different between the two divers. The International diver's mean curve illustrated a gradual increase in angular velocity, while the National diver illustrated a clear plateau in the rotation speeds. These present two different methods in solving the task constraint of high rotation speeds, which can either benefit or inhibit the overall performance outcome measures of total flight angular displacement and entry posture. The effect of the different somersault plateau structures will be discussed further in relation to performance variables correlations.

Correlations between fPCs and discrete performance measures

As hypothesised, the individual divers presented with their own unique types and number of significant correlations (International = 6; National = 8) when performing the forward 3½ pike somersault dive. Degree of performance success can, therefore, be considered as being associated with the amount of angular velocity variability. Previous research (Chapter 5) identified the International diver to have greater consistency in performance and a smaller magnitude of variability. Due to the ability to produce a similar movement structure over multiple repeated performances, it is not surprising that only six significant correlations were reported. Contrastingly, the National diver was seeking out multiple different coordination patterns as she learns to construct a successful forward 3½ pike somersault sequence. In search for the appropriate coordination pattern, greater inconsistency of angular velocity is presented resulting in a greater number of significant correlations with discrete kinematic variables. Performance specific correlations will be discussed below according to each individual diver.

International diver

*f*PC1 correlated with the performance outcome measures of total flight angular displacement, entry body alignment and entry hip angle. This particular *f*PC represented the highest variability (35%) within the International diver's angular velocity curves and was related to the amount of angular velocity achieved during the Somersault phase. The presence of a constant gradual increase in her patterns of the angular velocity, demonstrates that she is continuing to decrease her mass moment of inertial by adapting her body orientation to form a tighter pike position (greater hip and trunk flexion). However, for some dive performances where slower rotational speeds were achieved (negative scorers), this diver may have (1) not produced enough angular momentum prior to takeoff and/or (2) been unable to resist the high centrifugal forces acting on her body (Miller, 2013), resulting in a more open piked position (larger mass moment of inertia). These slower rotational speed dives affected the degree of performance success with less Total Flight angular displacement and a "shorter" entry (not vertical) on hand impact with the water.

The rate of hip extension during the final portion of the movement sequence also related to the success of entry body alignment. *f*PC2, indicated that negative scoring dives were associated with a quicker rate of hip extension, which was represented by the more rapid angular deceleration (Figure 20 - 1B). This correlated to negative scoring dives resulting in a more vertical entry body alignment ($r = 0.66$, $p = 0.036$). This *f*PC presented the ability of the International diver to make final adjustments prior to water entry to improve performance success.

Variation of the rate of rotation during the Initial Flight was related to the downward displacement of the springboard during the takeoff approach (*f*PC3) and peak dive height (*f*PC4). Higher rotational speeds during the Initial Flight were a result of greater maximum depression of the springboard. However, higher rotational speeds reduced the dive height from the springboard. Previous research has identified that for higher rotational speeds, a greater ratio of elastic strain energy that is produced during maximum depression is converted to horizontal velocity on takeoff (Sanders & Wilson, 1988). This suggests the higher rotational speeds during Initial Flight resulted in less vertical velocity on takeoff, reducing the vertical translation and height attain during dive flight.

National diver

The higher number of correlations for the National diver's angular velocity *f*PCs and performance kinematics identified technical movement characteristics requiring improvement. The more variable nature of the National diver's angular velocity curves from trial to trial did not present a clear pattern of performance that demonstrated how this diver could achieve sufficient angular displacement prior to water entry. Rotational speeds above and below the mean angular velocity were able to achieve similar levels of total flight angular displacement; therefore, other kinematic variables may be affecting the amount of angular displacement achieved.

*f*PC1, *f*PC2 and *f*PC5 represented 81% of the variability within the National diver's angular velocity curves and these were directly correlated to the linear performance kinematics. *f*PC1 and *f*PC2 demonstrated that dive performances with higher rotational speeds resulted in less dive height, less total flight duration and greater distance from the springboard. In contrast, *f*PC5 illustrated that higher rotational speeds during the Initial flight and Somersault phases less travelled a shorter distance from the springboard. This can be considered a positive linear performance association according the task constraints prescribed by FINA (2014). However, even though some repetitions of her 3½ pike somersault dive were associated with greater rotational speeds and flight durations, angular deceleration began at an earlier time point for these particular dives (Figure 21 - 2E) and therefore no benefits were achieved in terms of total flight angular displacement or a more vertical entry body alignment.

A smaller portion of variability (13%) in the National diver's angular velocity curves was represented by *f*PC3. This was the only *f*PC associated with the degree of success of the entry body alignment. *f*PC3 demonstrated that dive performances with greater maximum depression produced greater rotational speeds and a more vertical entry posture. The increased maximum depression can result in greater energy being returned to the diver for use in dive flight (Sanders & Wilson, 1988). The National diver's entry body alignment was also considered as short (160.0° ± 6.8%; Chapter 4) and therefore it may be that this diver needs to improve her approach mechanics in order to gain a more vertical for entry alignment (Barris et al., 2014).

The nature of the National diver's larger magnitude of variability (Chapter 5) and more significant correlations for the forward 3½ pike somersault dive aligns itself with Newell's (1985) outlook on the stages of learning. Here, this particular diver is still learning how to create the required coordination patterns to produce the forward 3½ pike somersault dive. Therefore, as this diver is searching for appropriate coordination patterns, higher levels of random variability (Button et al., 2003; Wilson et al., 2008) and less successful performance outcomes were seen from trial to trial when compared to the performances of the International diver. Due to the larger number of correlations between angular velocity *f*PCs and linear kinematics (discussed above), it can be proposed that the National diver may be increasing the ratio of energy being used for angular kinematics as she strives to achieved to high rotational demands of this task. Therefore, she may be sacrificing the development of linear translation to obtain adequate dive height and time of flight. Over time with practice we, however, suspect she will learn how link and coordinate both the linear and angular task demands.

Conclusion and Perspectives

These findings highlight the importance of the examining individuals in order to understand their typical structure of performance as well as determine how deviations from this structure can enhance or inhibit their performance outcomes. Applying *f*PCA to each individual's repeated measures of angular velocity curves helped to preserve the natural structure and characteristics that might otherwise have been lost when data is combined for between-participant analysis (e.g., Chapter 5). Specifically for the current study, within-participant analysis highlighted two separate categories of kinematics (International = angular; National = linear) where optimisation can be achieved for performance success. The International diver's success was largely determined by the amount of angular velocity achieved during the Somersault phase and the National diver's success can be improved via stability of positive linear kinematics (i.e., dive height and duration). The combined analysis procedures showcased the feasibility of within-participant research designs for multiple sporting contexts in understanding the intricate and unique nature of individual athletes to optimise technique, reduce performance error and improve overall skill.

References for this chapter are included in the list of references at the end of this thesis

CHAPTER 7

Discussion and Thesis Conclusion

Overview of main findings

The primary objective of the current body of work was to implement modern technology in the analysis of springboard diving, with the aim to provide a more holistic approach when examining individual divers' rotational pattern movement structure, variability and consistency. Firstly, inertial measurement units (IMUs) were introduced in an attempt to more efficiently collect and analyse data of multiple somersault dives from the 3m springboard. IMUs time-series data provided the opportunity to move away from customarily discrete kinematics analysis (e.g., mean ± SD) and employ a more holistic analysis technique. The contemporary statistical technique of functional principal component analysis (*f*PCA) was applied to angular velocity time-series to quantify the structure (shape change) and magnitude (amount) of variability within individual divers. The primary findings of the current body of work were as follows:

- Gyroscopes embedded in ImeasureU® water proof IMUs produce accurate data with mean percentage differences between an optical tracking system (Cortex 3.3) being within 0.5% ($p < 0.05$) for angular velocity and 1.0% for total change in angular displacement (Chapter 3).
- To achieve the hardest dive currently being performed (4½ tuck somersaults), divers need to delay rotation immediately after takeoff to gain greater vertical translation and time of flight, be able to produce high rotation velocities (mean - 1090deg/s; maximum recorded - 1160deg/s) and have adequate muscular strength to maintain and control the somersault position (Chapter 3).
- As dive degree of difficulty increased, within-participant variability (measured as CV%) decreased for angular velocity, angular displacement and duration during the Initial Flight and Somersault phases. Contrastingly, the within-participant variability

of angular displacement and duration for the Opening Flight phase increased (Chapter 4).

- Total flight angular displacement and duration was highly consistent (0.5-2.1%) and reflected the diver's ability to use a feedback control strategy to functionally adapt the timing and rate of angular deceleration during the Opening phase in response to the previous phases of the dive flight (Chapter 4).
- Entry posture became more inconsistent as dive degree of difficulty increased and was susceptible to minor variations within the amount of total rotation achieved in higher degree of difficulty dives (3½ and 4½ somersaults) (Chapter 4).
- *f*PCA demonstrated that the lower skilled (National level) diver was associated with a random structure of angular velocity performance, larger magnitudes of variability and a larger number of significant correlation between angular velocity and performance kinematics (determinates of performance success) (Chapter 5 and Chapter 6).
- *f*PCA demonstrated that the higher skilled (International level) diver was associated with a more stable structure of angular velocity performance, lower magnitude of variability and a smaller number of significant correlations between angular velocity and performance kinematics (Chapter 5 and Chapter 6).
- Performance of the lower skilled diver was most likely associated with the diver learning the coordinate and link the multiple phases of dive flight (Chapter 4, 5 and Chapter 6).
- Greater stability in performance for the International divers was linked to being more proficiently trained at using aerial awareness and a prospective feedback back strategy, allowing more experienced divers the ability to functionally adapt and control their angular velocity throughout the entire movement sequence (Chapter 4, 5 and Chapter 6).

- Greater angular velocity during the Initial Flight and/or Somersault phases correlated to a more vertical aligned entry posture for both skill levels of female divers (Chapter 6).

Implications

Technology

Biomechanical research of springboard diving has been largely limited to two-dimensional video analysis, due to the expense and impracticality of three-dimensional motion analysis (e.g., set up and markers falling off on water entry). The current body of work was the first to apply inertial measurement units to the sport of springboard diving (Sinclair et al., 2014; Walker et al., 2014). The positive features of the chosen IMeasureU® units corresponded with previous research that have used similar technology (e.g., Gouwanda and Senanayake (2008)). These features include; low cost, small in size, light weight, non-invasive, wireless, ecologically valid, time efficient and waterproof. In comparison with a three-dimensional optical system (Cortex 3.3 Motion Analysis Corporation, USA) gyroscopes embedded within the IMeasureU® units produce similar output kinematics for angular velocity (<0.5% difference). Similarly, drift associated with integrating IMU angular velocity times-series to calculate the change in angular displacement was negligible, with <1.0% difference between the optical system over a duration of 6.4±2.5s. Data analysis proved to be more efficient and provided the opportunity to collect and analyse a greater number of dive performances per individual than have previously been reported. This allowed a better understanding of the unique nature of springboard divers performing a range of aerial manoeuvers from relatively basic to highly difficult.

Study design

The current body of work demonstrated the implications of applying a within-participant study design. Individuals interpret, react, and adjust their movement coordination patters differently according to physical, environmental and task specific constraints that are imposed on the human body (Newell, 1986). The common discussion throughout previous research is that no two movement patterns are alike, let alone no two individuals (Bartlett et al., 2007; Bates, 1996; Brisson & Alain, 1996; Davids et al., 2003; Mullineaux et al., 2001; Newell & Slifkin, 1998). The current body of work supports these findings and discussions. Individual springboard divers presented their own unique structures of movement patterns and had different abilities to adapt to perturbations within these movement patterns.

Springboard diving is predominately an individual sport where judges produce scores from their perceived success of the skill performed. Historically, biomechanical researchers of springboard diving have reduced an individual's performance template by averaging group data and producing norms for how specific dives are performed (Hamill et al., 1986; Miller et al., 2002; Sanders & Gibson, 2000; Sanders & Wilson, 1988). Group study designs have provided the common performance characteristics of international divers, however, they limit the ability of the researchers to provide important performance feedback to coaches and sport service providers (e.g., strength and conditioning), whose primary roles are to produce the best athlete possible. The research throughout this body of work increased the number of trials collected per dive, which provided a more holistic evaluation of individuals motor behaviour (Dona et al., 2009) and demonstrated unique within-participant differences of springboard divers. Practical implications of within-participant study designs were proved to be important in understanding individual techniques, strategy and adaptability in order to identify performance weaknesses and strengths.

Functional principal component analysis

When examining the ability of athletes to coordinate and control multiple phases of a movement sequence, Chapter 4 limited the amount of information according to movement variability across multiple angular velocity curves. This was due to selecting pre-determined discrete measures (i.e., Initial flight, Somersault and Opening phase; change in angular displacement, duration and angular velocity) and calculating the relative variability (CV%) of these. Repetitions of dive performances presented a consistent Total Flight angular displacement (0.5-1.2%), however the structure of the angular velocity curve that created this outcome consistency could be very different (Newell & Slifkin, 1998). Movement variability presented in Chapter 4, therefore was not representative of the nature of the continual movement sequence but of the deviation from the mean of the pre-determined kinematics. Functional principal component analysis (*f*PCA) proved influential in analysing the wave-form data produce by the IMU gyroscopes. *f*PCA provided the ability to move from qualitatively describing individuals typical pattern of angular velocity performance and calculating relative variability (CV%) of pre-determined kinematics, to quantifying where the differences were from the mean line of multiple time-series trials (Dona et al., 2009; Donoghue et al., 2008; Ryan et al., 2006).

*f*PCA analysed the entire angular velocity sequence as one entity and *f*PC scores signified areas where movement variability occurred across the time-series data for individual divers. Specific characteristics and differences within and between-participants were influential in identifying the intricate and unique nature of divers to optimise technique, reduce performance error and improve overall skill. *f*PCA can be applied across multiple human movement contexts to monitor performance over time and understand an athlete's ability to functionally anticipate and adapt perturbations to produce a successful skill.

Movement variability

The dynamical systems theory acknowledges that as skill level increases movement variability will increase, providing functional adaptation strategies within the motor system to manipulate a movement sequence (Bartlett, 2008; Schorer et al., 2007; Wilson et al., 2008). The dynamical systems theory focuses on the intricate nature of coordinating degrees of freedom within, for example; lower extremities (Hamill et al., 1999), where the system is flexible to process and adapt to the demands of physical, environmental and task constraints (Newell, 1986). However, the nature of the current body of work did not present data based upon process measures (e.g., coordination synergies between joints kinematics), but key continuous and discrete performance measures of springboard diving. These measures encompass the whole body's degrees of freedom and the underlying processes of coordinative structures that inherently produce these performance metrics. Therefore we need to re-consider the way we view variability when analysing more global kinematic measures.

Springboard diving is a closed-sport (Highlen & Bennett, 1983), where the task prescribes a definitive start and end (takeoff to water entry). The theory of increased variability as skill level increases provides a false impression for the nature of kinematic measures during a diving task, particularly when coaches are continually instructing their athletes to produce consistent repetition of dive performances. Opposing the dynamical systems theory, our International level divers presented less variability for their highest degree of difficulty dive performed for both continuous angular velocity curves and discrete kinematic measures (Chapter 4, 5 and 6). Even though all divers were considered highly skilled, our National level diver had been performing her hardest dive for a significantly less duration of time (1 month) when compared to our International divers (≥ 2 years). She was, therefore, considered under the *coordination* phase of learning for this particular dive (Newell, 1985). During the early phases of learning the movement sequence for the 3½ pike somersault dive, greater magnitudes of variability occurred as the National diver explored and developed appropriate movement coordination patterns (Button et al., 2003; Wilson et al., 2008) to link the multiple phases of flight. The International divers demonstrated that over time, experience has taught them how to control the appropriate coordination patterns to more successfully produce difficult dives.

When examining the relationship of variability in angular kinematics with discrete performance measures, the National diver presented a greater number of significant correlations when compared to the International divers. The reduced number of significant correlations presented by the International divers directly relates to the consistency found in both the continuous and discrete kinematic measures (Chapter 4 and 6). Chapter 6, examined the link between key performance kinematics (discrete) and angular velocity time-series (continuous), providing a more holistic understanding of the skill for the individual diver. These demonstrated that the National diver was not able to coordinate and link the linear and angular elements required to perform the 3½ pike somersault dive. While she was able to achieve consistent high rotational speeds (886.6 ± 7.0 deg/s; CV = 0.8%), her inability to achieve consistently enough energy (maximum depression), dive height and dive duration (Table 16), reflects why greater inconsistencies were presented in her overall angular velocity movement sequence and performance outcome success.

Even with higher movement sequence consistency, the International divers presented some levels of variability, which follows the dynamical systems concept that variability is functional in helping to complete a successful task. For the current study we considered this variability as functional control, emerging from a feedback strategy. For the highest degree of difficulty dives, Opening phase angular velocity (Chapter 5 and 6), duration and change in angular displacement (Chapter 4) variability increased. This variability presented adaptation in response to any dysfunctional variability during the first two phases of flight. Similar to previous research in gymnastics (Bardy & Laurent, 1998), divers were most likely using perspective (visual) feedback alongside trained aerial awareness to adapt the initiation and rate of angular deceleration. The evidence from the current investigations presented that the International divers were more proficiently trained in understanding and using this feedback, which was most likely due to the number of years practicing this dive.

Table 16. Linear performance kinematics; mean ± SD (CV%)

Linear Performance Measure	**International (male)**	**International (female)**	**National (female)**
Maximum depression	0.75 ± 0.01m (1.7%)	0.78 ± 0.01m (1.8%)	0.70 ± 0.02m (3.0%)
Dive height	1.71 ± 0.05m (2.9%)	1.13 ± 0.03 (2.5%)	0.98 ± 0.09m (9.4%)
Dive Distance	2.05 ± 0.15m (7.3%)	2.37 ± 0.17m (7.0%)	1.87± 0.14m (7.6%)
Opening Flight duration	0.22 ± 0.01s (6.1%)	0.22 ± 0.01s (6.5%)	0.18 ± 0.04s (20.0%)
Total Flight duration	1.59 ± 0.01s (0.5%)	1.39± 0.01s (0.5%)	1.36 ± 0.03s (2.1%)

Tables notes: International male - 109C (n = 6); International female - 107B (n = 10); National female - 107B (n = 10).

When examining movement variability, researchers need to consider the type of the movement (open or closed) and the variables of interest as this can impact the perception for what type of variability is hypothesised to be presented. For example, increased variability has been presented and accepted as being functional for open-sporting contexts such as handball, hockey and squash, where athletes must adapt to uncontrollable environmental constraints such as ball impact velocity and trajectories (Burgess-Limerick et al., 1991; Schorer et al., 2007; Wollstein & Abernethy, 1988). Increased variability of intra-limb joint couplings has also been presented as functional in adapting to perturbations during gait movement patterns (Hamill et al., 1999; Wilson et al., 2008) and upper-limb coordination for target shooting (Arutyunyan et al., 1968; Button et al., 2003). In contrast, closed sporting contexts such as gymnastics (Bardy & Laurent, 1998; Gittoes et al., 2011; Lee et al., 1992) and springboard diving, may accept a more traditional motor learning perspective, in the context of stability in performance outcome measures (i.e., amount of rotation achieved and safe landing/entry posture) for highly skilled athletes. Researchers therefore need to take into consideration: (1) the fundamentals of the movements they are assessing (closed or open) and (2) nature of variables of interest (performance outcomes, joint couplings etc.) before determining what type of variability (error, stability, adaptation etc.) they expect to be examining and how variability is expected to change with development of skill.

Thesis limitations and delimitations

Two limiting factors of the current body of work were the technology and participant sample size. While IMUs were the foundation of data collection, delivery of this technology was delayed resulting in a reduced amount of time to collect data. Secondly, the IMUs used were prototypes that had yet to be released for commercial use. This meant no user manual or troubleshooting had been published. Problems that occurred with the units included:

- Not charging on induction pad
- Not turning on over wireless network
- Not turning off over wireless network

To overcome such problems we had to work directly with the developing engineers. However the major issue that was not able to be solved due to the hermetically sealed nature of the units, was whether or not the units would turn on for the day of data collection. Therefore, we chose to only collect data from a single anatomical land mark (posterior superior iliac spine) due to these restrictions imposed by the technology.

Participant sample size was small for the current body of work. Elite springboard divers capable of performing the current high level of dive degrees of difficulties is rare worldwide, with only a small number of capable divers within Australia (i). The attendance of International athletes at training camps at the National training centre provided potential increases in sample size, however due to time constraints, data were only permitted to be collected on one day and on one dive degree of difficulty (4½ tuck somersault). Therefore, this was considered as pilot data (Sinclair et al., 2014; Walker et al., 2014) that was not sufficient for Chapters 3-6.

The male participant (Participant 1 in Chapters 3 and 4) was not taken forward for analysis in Chapters 5 and 6 due to the smaller number of dive trials performed of the forward 3½ pike and 4½ tuck somersault dive. Previous acrobatic research have reported sample sizes of 10 repetitions of movement to be acceptable when assessing movement variability (Farana et al., 2015; Gittoes et al., 2011; Hiley et al., 2013; Lee et al., 1992). Due to our male diver performing three dive degrees of difficulties, he performed a smaller number of repetitions of the 3½ pike somersaults to allow him to perform the 4½ tuck somersaults without overloading his body during training (prevent injury). This diver was also attending international training camp (separate to the athletes from the pilot data), which also restricted the number of data collection sessions.

This study examined an increase number of trials per participant than previously reported. Therefore unique and idiosyncratic characteristics of movement variability in angular velocity, angular displacement and flight phase durations were demonstrated. Consequently, findings cannot be easily extrapolated to other divers of similar and different skill levels as they present unique patterns of performance. That said, our methods and analytical approach allow sport scientists and practitioners the potential to more accurately assess individual movement technique, as well as identify performance limitations and areas for skill improvement.

Footnote i) ***Five*** *females in Australia are capable of performing the 3½ pike somersault dive. We were granted access to two*
One *male in Australia is capable of performing the 4½ tuck somersault dive. We did not have access to this athlete, but were granted access to an international athlete attending a training camp*

Directions for future research

The current body of work has set up multiple pathways for future research in a variety of difference contexts. To enhance the understanding of motor control and coordination of both intrinsic and global kinematics across multiple sporting contexts, IMUs and *f*PCA present the opportunity to monitor and analyse athletes' movement strategies and capabilities. In a sport such as springboard diving that has a relatively small number of highly skilled athletes, longitudinal studies can be conducted to examine junior elite divers' progressions from relatively easier dives to high standard international dives. Throughout this body of work potential research questions have arose, with areas of interest for future research being as follows:

Inertial Measurement Units

The development of an ecologically portable three-dimensional analysis system for springboard and platform diving can be feasible through the integration of gyroscopes, accelerometers and magnetometers. The application of multi-segment IMUs provides the opportunity to perform full body analysis in ecologically viable contexts. From the current body of work the following variables would be recommended to further increase the understanding of springboard divers' control and coordination capabilities during both the approach and dive flight:

- Joint angles and angle-angle coordination plots
- Whole body and segmental linear and angular velocities
- Whole body and segmental linear and angular accelerations
- Force and power development during the maximum depression
- Force on water entry at the wrists, elbows, shoulders and mid to lower back

Functional principal component analysis

In line with the above variables, *f*PCA can be used to statistically identify areas where skill can be improved as well as to monitor the development of functional control strategies. Areas of recommendation to further understand the above include:

- Coordination of joint couplings during the springboard approach - Examine divers' ability to produce a successful approach in terms of gait, hurdle, maximum depression, springboard recoil and takeoff.
- Coordination of joint couplings during the dive flight - Examine diver's ability to maintain a tight somersault position and the ability to coordinate rotation about two axis for twisting somersault dives.
- Development of functional control to produce sufficient angular displacement and a vertical entry posture
- The ability to determine when a diver has capability to increase the number of somersault revolutions

Injury

The repetitive nature of springboard diving results in a high risk for injury, in particular overuse injuries (Zimmermann, 2013) such as stress fractures of lumbar vertebra. Within Australia, Athlete Management Systems (AMS: Australian Sporting Commission) have been integrated to help monitor training loads and determine red flags for injuries. Currently, athletes input the number of repetitions of each dive performed and supply a rate of perceived exertion (RPE) for the overall training. However, personal observation of athletes on a weekly basis has shown that they do not always input data for each session. Individuals may also perceive the same training session load differently and therefore correlations may not necessarily be providing a true indication of injury risk factors. IMUs can be integrated into this system to potentially remove the individual's RPE. IMUs have the ability to be implemented into daily training routines, monitor training load and produce clear numerical data that can be correlated to injuries sustained during training. This numerical information can therefore be used provide further knowledge in the prevention of injury.

Conclusion

The first aim of this current body of work was to determine whether inertial measurement units (IMU) were able to accurately measure angular kinematics in order to apply them as a data collection apparatus for springboard diving. Comparison of IMUs with a laboratory based three-dimensional optical tracking system (Cortex 3.3 Motion Analysis Corporation, USA) reported accurate gyroscope output measures. Percentage differences between the two systems was minimal, with <0.5% difference between the two systems for angular velocity and <1.0% difference in the accumulated drift when integrating the angular velocity signal to calculate change in angular displacement.

Subsequently to the first aim, IMUs were successfully integrated into springboard divers' training sessions. This allowed an increased number of trials to be collected per individual and per dive degree of difficulty than have previously been reported. IMUs demonstrated that as forward dive degree of difficulty increased, angular velocity significantly increased ($p < 0.001$) to achieve adequate angular displacement. To perform the most difficult dive currently being performed by (male) divers internationally (4½ tuck somersaults), IMUs demonstrated that a successful performance is achieved by: (1) development of greater total flight durations (1.59 ± 0.01s; $p = 0.008$), indicated by a rotational delay directly after takeoff,

(2) development of high rotational speeds (max = 1160 deg/s) and (3) the ability to control these high rotational speeds.

The third and fourth aims of this body of work were to examine within-participant movement variability during the dive flight as well as to determine how dive difficulty and skill level effect this variability. As dive degree of difficulty increased all divers demonstrated a decrease in movement variability of their angular velocity time-series and pre-determined discrete kinematics during the Initial Flight and Somersault phases. For the relatively easy 1½ pike somersault dive, divers had a greater total time of flight to create, manipulate and adapt their movement sequence. However, when performing an additional 2-3 somersault revolutions, time of flight reduced and therefore divers had smaller time windows to explore and manipulate their movement sequence, thus requiring more stability within the movement sequence. Perspective feedback and aerial awareness control strategies were evident across all divers, with Opening flight movement variability increasing as dive degree of difficulty increased. This was considered a functional strategy where divers adapted the commencement and rate of angular deceleration according to the first two phases of flight. This functional strategy allowed divers to achieve consistent total flight angular displacement (CV = 0.5-0.8%) during the more difficult dives.

The International skilled divers in this study were associated with greater consistency in both discrete kinematic measures (CV%) and angular velocity time-series. *f*PCA demonstrated lower magnitudes of variability (standard deviations) in repeated measures of the forward 3½ pike somersault dive and therefore greater stability within the International diver's angular velocity movement sequences. The higher levels of movement variability presented by the National diver were attributed to being under the *coordination* phase of learning (Newell, 1985), where higher levels of random variability were seen as she learned to coordinate the required movement sequence.

The final aim of this body of work was to determine how movement variability of angular kinematics during the most difficult dives performed by males (4½ tuck) and females (3½ pike) affected key discrete kinematics of dive execution. In examining correlations between a range of kinematic variables and entry body alignment, two common significant correlations were presented amongst the divers: (1) Total Flight angular displacement and (2) angular velocity achieved during the Initial flight and/or Somersault phase. Additional significant correlations demonstrated that each individual had their own unique number and type of performance kinematics that correlated to the success of dive execution (e.g., Total Flight angular displacement and entry body alignment). The International divers' significant correlations were associated with angular kinematics (e.g. Somersault phase angular velocity and/or duration), while the National diver's significant correlations were associated with linear kinematics (e.g., Total Flight duration and dive height). The differences in significant correlations were postulated to the National diver learning how to link and coordinate both the angular and linear requirements of the 3½ pike somersault dive.

Within-participant study designs, in particular for springboard diving where coaches are continually instructing divers to repeat successful dive performances, are important to understand the underlying nature, technique and strategies of unique individuals. It is recommended that future research should move from between-participant study designs, which produce normative values of performance, to within-participant designs to more proficiently examine individual performance, optimise technique, reduce performance error and improve overall skill.

References for this chapter are included in the list of references at the end of this thesis

APPENDIX

List of appendices

Appendix 1
FINA diving rules

Diving rules related to the forward dive category

Section 8 - Judging, accessed from FINA (2014, pp. 226-230)

D 8 JUDGING

D 8.1 General

D 8.1.1 A judge shall award from 0 to 10 points for a dive according to his overall impression within the following criteria:
Excellent 10
Very Good 8.5 – 9.5
Good 7.0 – 8.0
Satisfactory 5.0 – 6.5
Deficient 2.5 – 4.5
Unsatisfactory 0.5 – 2.0
Completely failed 0

D 8.1.2 When judging a dive, the judge must not be influenced by any factor other than the technique and execution of the dive. The dive must be considered without regard to the approach to the starting position, the difficulty of the dive, or any movement beneath the surface of the water.

D 8.1.3 The points to be considered in judging the overall impression of a dive are the technique and grace of:
– the starting position and the approach
– the take-off
– the flight
– the entry

D 8.1.4 When a dive is performed clearly in a position other than that announced the dive shall be deemed unsatisfactory. The highest award for such a dive is 2 points.

D 8.1.5 When a dive is performed partially in a position other than that announced, the judges shall exercise their own opinion in making their award up to a maximum of 4½ points.

D 8.1.6 When a dive is not performed in the straight (A), pike (B), tuck (C), or free (D) position, the judge shall deduct from ½ to 2 points, according to his opinion.

D 8.1.7 When a judge considers that a dive of a different number has been performed he may award zero (0) points, notwithstanding that the Referee has not declared it to be a failed dive.

D 8.2 The starting position

D 8.2.1 When the signal is given by the Referee, the diver shall take the starting position.

D 8.2.2 The starting position shall be free and unaffected.

D 8.2.3 When the correct starting position is not free and unaffected, each judge shall deduct ½ to 2 points, according to his opinion.

D 8.2.5 Running dives

D 8.2.5.1 The starting position in a running dive shall be assumed when the diver is ready to take the first step of the run.

D 8.3 The approach

D 8.3.1 When executing a running dive from either the springboard or the platform, the run shall be smooth, aesthetically pleasing, and in a forward direction to the end of the springboard or platform with the final step being from one foot.

D 8.3.2 When the run is not smooth, aesthetically pleasing, or in a forward direction to the end of the springboard or platform, each judge shall deduct ½ to 2 points, according to his opinion.

D 8.3.3 When the final step is not from one foot, the Referee shall declare a failed dive.

D 8.3.4 The diver must not double bounce on the end of the springboard or platform before the take-off. When the judge considers that the diver has double bounced in a dive, the judge may award zero (0) points, notwithstanding that the Referee has not declared it to be a failed dive.

D 8.4 The take-off

D 8.4.1 The take-off in forward and reverse dives may be performed either standing or running at the option of the diver. The take-off in backward and inward dives must be performed standing.

D 8.4.2 The take-off from the springboard shall be from both feet simultaneously.

The forward and reverse take-off from the platform may be from one foot.

D 8.4.3 When the take-off from the springboard is not from both feet simultaneously, the Referee shall declare it a failed dive.

D 8.4.4 In running and standing dives, the take-off shall be bold, high and confident, and shall be from the end of the springboard or platform.

D 8.4.5 When the take-off is not bold, high and confident, or from the end of the springboard or platform, each judge shall deduct ½ to 2 points, according to his opinion.

D 8.4.6 In dives with twist, the twisting shall not be manifestly done from the springboard or platform. If the twisting is manifestly done from the springboard or platform, each judge shall deduct ½ to 2 points, according to his opinion.

D 8.5 The flight

D 8.5.1 If during the execution of a dive, a diver dives to the side of the direct line of flight, each judge shall deduct according to his opinion.

D 8.5.2 If during an execution of a dive, a diver touches the end of the springboard or platform with his feet or hands, each judge shall deduct according to his opinion.

D 8.5.3 If during the execution of a dive, a diver is unsafely close to the springboard or platform or touches the end of the springboard or platform with his head, the judges shall award up to a maximum of 2 points. If the majority of the judges (at least three (3) in a 5 judge panel / at least four (4) in a 7 judge panel) award two (2) or less points, all higher scores shall be two (2) points.

D 8.5.4 During the flight, the position of the dive shall be at all times aesthetically pleasing. Should any of the positions not be shown as described below, each judge shall deduct ½ to 2 points, according to his opinion.
The dive can be executed in the following positions:

Straight (A)
D 8.5.5 In the straight position the body shall not be bent either at the knees or hips. The feet shall be together and the toes pointed. The position of the arms is at the option of the diver.

D 8.5.6 In all flying dives a straight position shall be clearly shown and that position shall be assumed from the take off or after one somersault. When the straight position is not shown for at least one quarter of a somersault (90º) in dives with one (1) somersault, and at least one half of a somersault (180°) in dives with more than one (1) somersault, the maximum award by the judges shall be 4½ points.

Pike (B)

D 8.5.7 In the pike position the body shall be bent at the hips, but the legs must be kept straight at the knees, the feet shall be together, and the toes pointed. The position of the arms is at the option of the diver.

D 8.5.8 In the pike dives with twist, the pike position must be clearly shown. Should this position not be shown, each judge shall deduct ½ to 2 points, according to his opinion.

These diving illustrations serve as a guide only and the position of the arms is at the choice of the diver except in the entry.

Tuck (C)

D 8.5.9 In the tuck position the body shall be compact, bent at the knees and hips with the knees and feet together. The hands shall be on the lower legs and the toes pointed.

D 8.5.10 In tuck dives with twist, the tuck position must be clearly shown. Should this position not be shown, each judge shall deduct ½ to 2 points, according to his opinion.

These diving illustrations serve as a guide only and the position of the arms is at the choice of the diver except in the entry.

D 8.6 The entry

D 8.6.1 The entry into the water shall in all cases be vertical, not twisted, with the body straight, the feet together, and the toes pointed.

D 8.6.2 When the entry is short or over, twisted or the body not straight, the feet not together, and the toes not pointed, each judge shall deduct according to his opinion.

D 8.6.3 In head first entries, the arms shall be stretched beyond the head and in line with the body, with the hands close together. If one or both arms are held below the head on entry, the Referee shall declare a maximum award of 4½ points.

D 8.6.4 In feet first entries, the arms shall be close to the body with no bending at the elbows. If one or both arms are held beyond the head on entry, the Referee shall declare a maximum award of 4½ points.

D 8.6.5 Other than as provided in Rules D 8.6.3 and D 8.6.4, when the arms are not in the correct position in either the head first or feet first entry, each judge shall deduct from ½ to 2 points, according to his opinion.

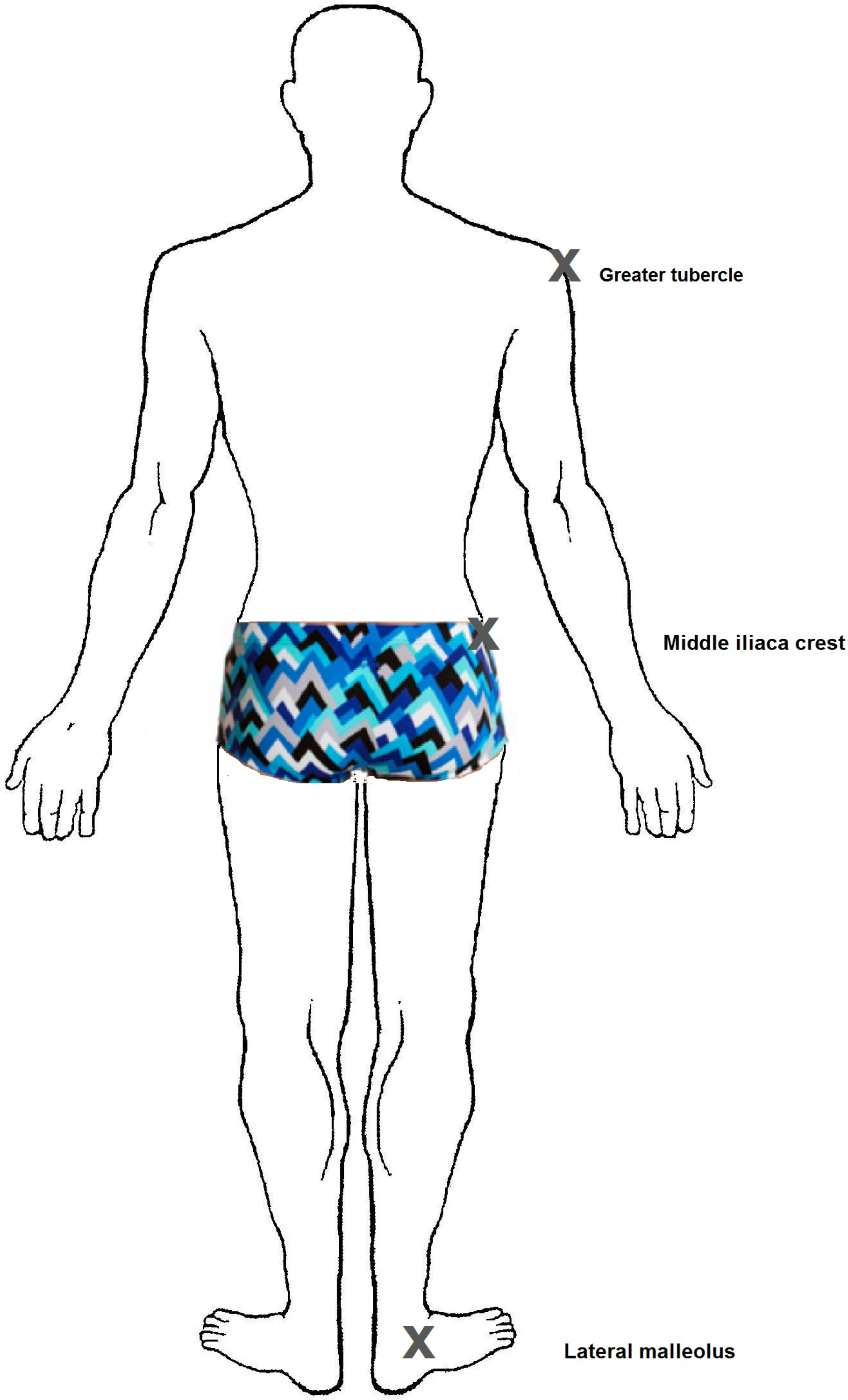
D 8.6.6 When a twist is greater or less than that announced by 90 degrees or more, the Referee shall declare it a failed dive

D 8.6.7 The dive is considered to have been completed when the whole of the body is completely under the surface of the water.

Appendix 2
Anatomical location of IMU

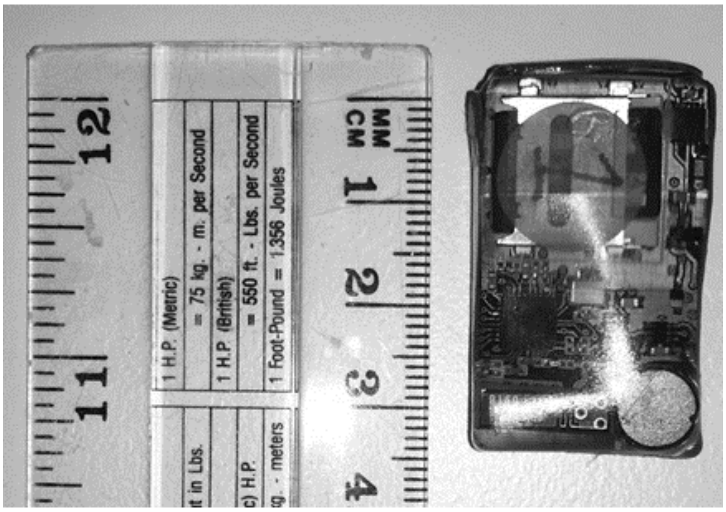
Anatomical landmarks

Two-dimensional video footage digitised landmarks.
Note: landmarks were only required for the side of the body that was facing the camera



Appendix 3
Additional IMU validation information

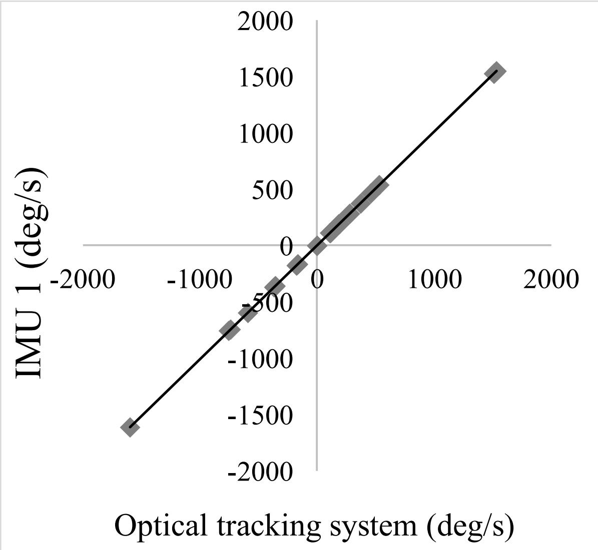
Inertial measurement unit develop by ImeasureU®.

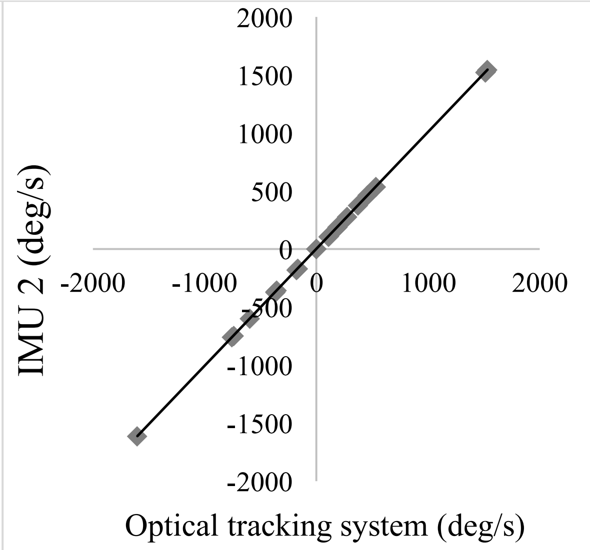


Drill speed, range and Butterworth filter for the 3D motion analysis data

Drill Speed	Speed range	Butterworth filter (Hz)
Slow	108 - 191 deg/s	1
Medium	189 – 372 deg/s	2
Fast	375 – 760 deg/s	4
Maximum	1523 – 1613 deg/s	7

Individual IMU units' linear regressions between the Optical Tracking System (Cortex 3.3, Motion Analysis Corporation, USA)



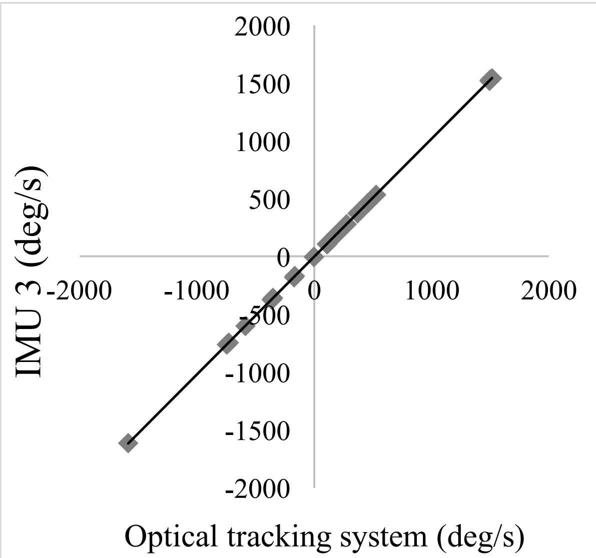


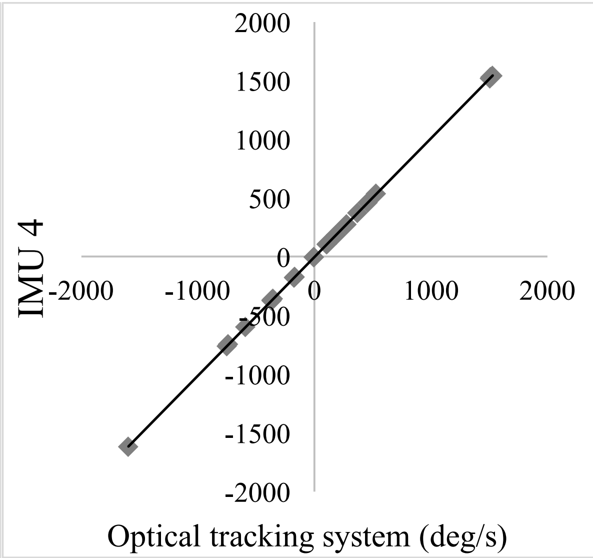
IMU 1

y = 1.0096x - 0.3854
R^2 = 1. .000

IMU 2

y = 1.0081x - 0.2703
R^2 =1.000





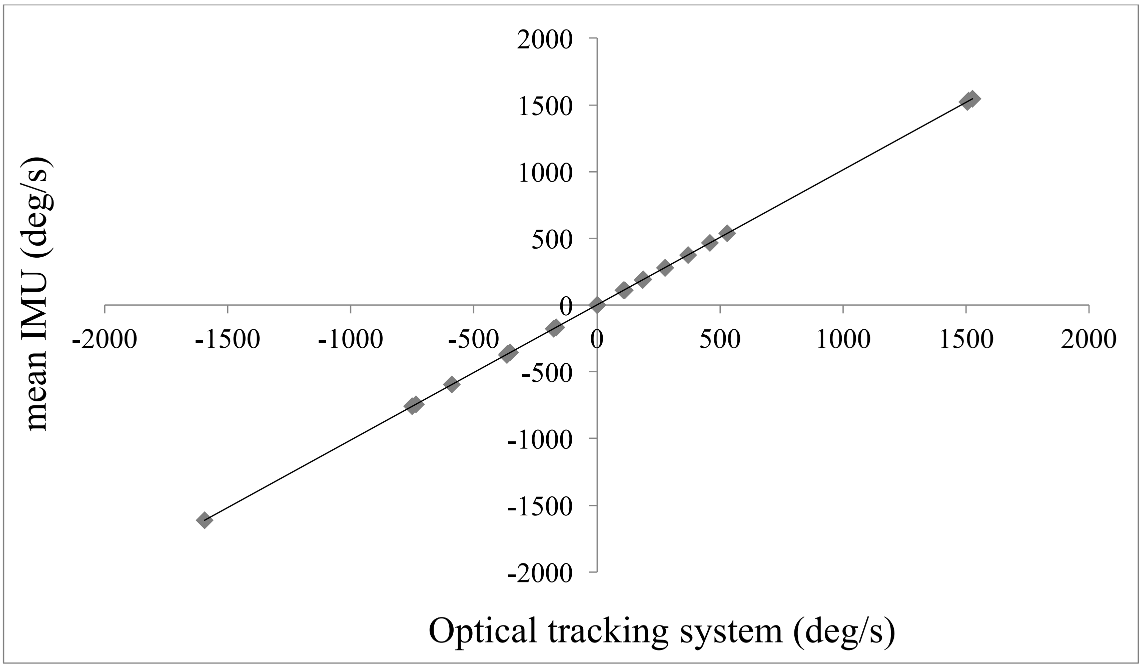
IMU 3

y = 1.019x + 0.4378
R^2 = 1.000

IMU 4

y = 1.0113x + 0.0852
R^2 = 1.000

Mean IMU linear regression between then Optical Tracking System (Cortex 3.3, Motion Analysis Corporation, USA)



Mean
$y = 1.012x - 0.0344$
$R^2 = 1.000$

Angular velocity percentage differences between IMUs and Optical tracking system (Cortex 3.3, Motion Analysis Corporation, USA).

IMU	Non-calibrated	Individual IMU Calibration	Mean calibration	Significance (*p* – value)
S1	0.98 ± 0.26%	0.42 ± 0.59%	0.41 ± 0.49%	0.000
S2	1.08 ± 0.38%	0.20 ± 0.38%	0.19 ± 0.35%	0.000
S3	0.88 ± 0.22%	0.29 ± 0.51%	0.55 ± 0.60%	0.012
S4	1.86 ± 0.35%	0.19 ± 0.37%	0.73 ± 0.20%	0.000
Mean	**1.21 ± 0.50%**	**0.25 ± 0.44%**	**0.47 ± 0.47%**	

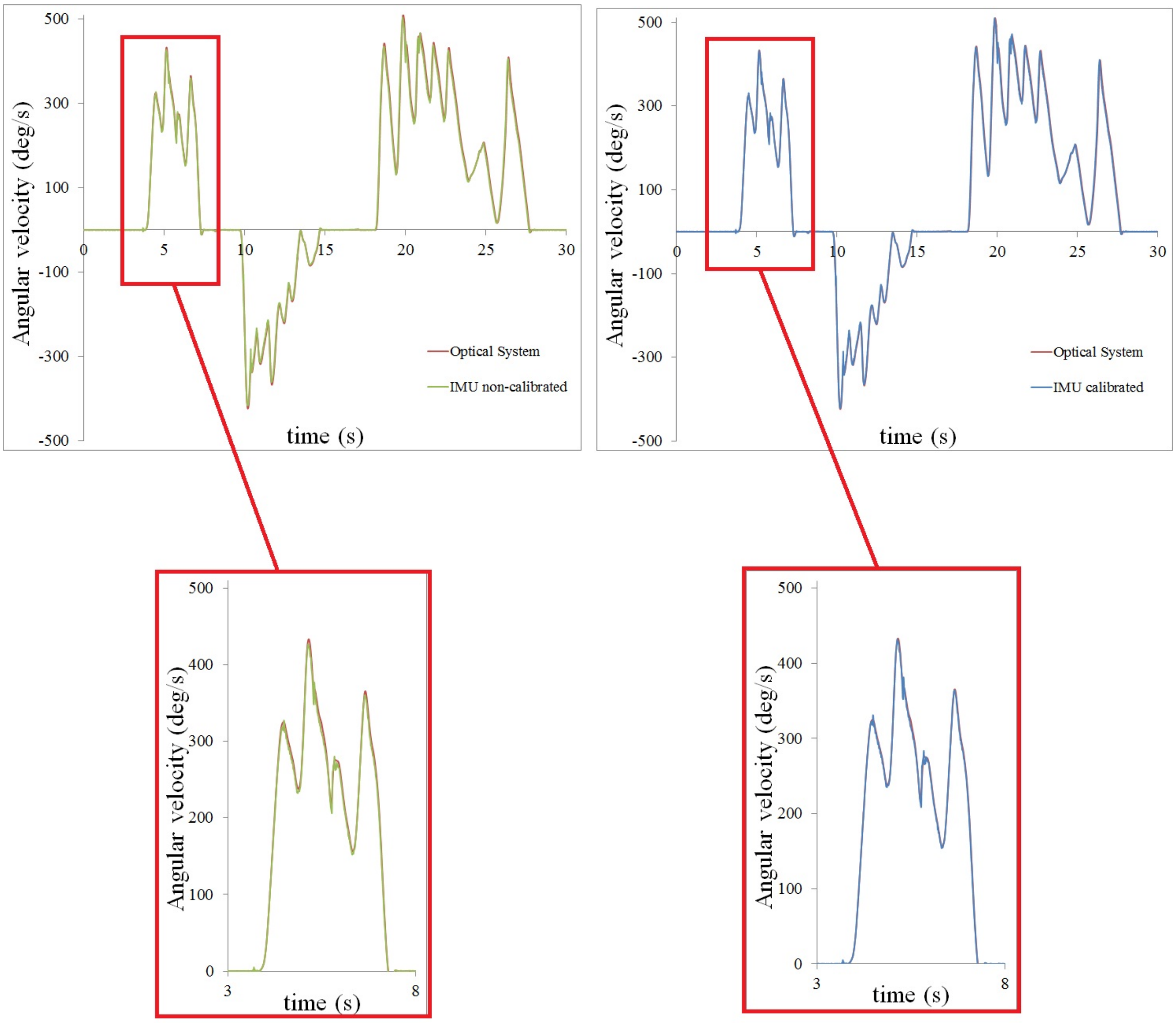
Table notes: Calibration refers to the linear regression equation applied to the raw IMU angular velocity data

Significant refers to the independent t-test between the non-calibrated and mean calibration percentage differences

Angular velocity visual comparison between IMU and Optical System

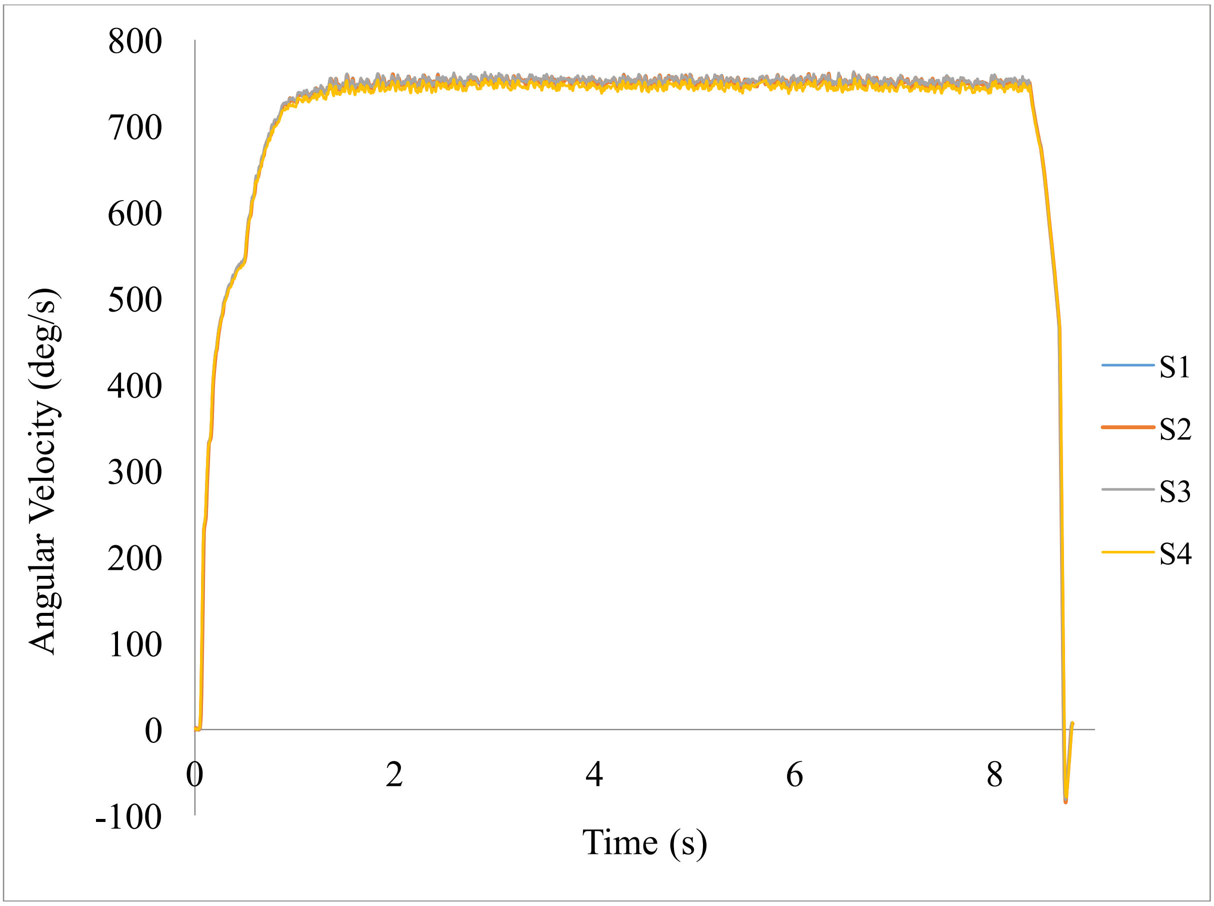
Example: IMU 1

No calibration equation applied | Mean Calibration equation applied



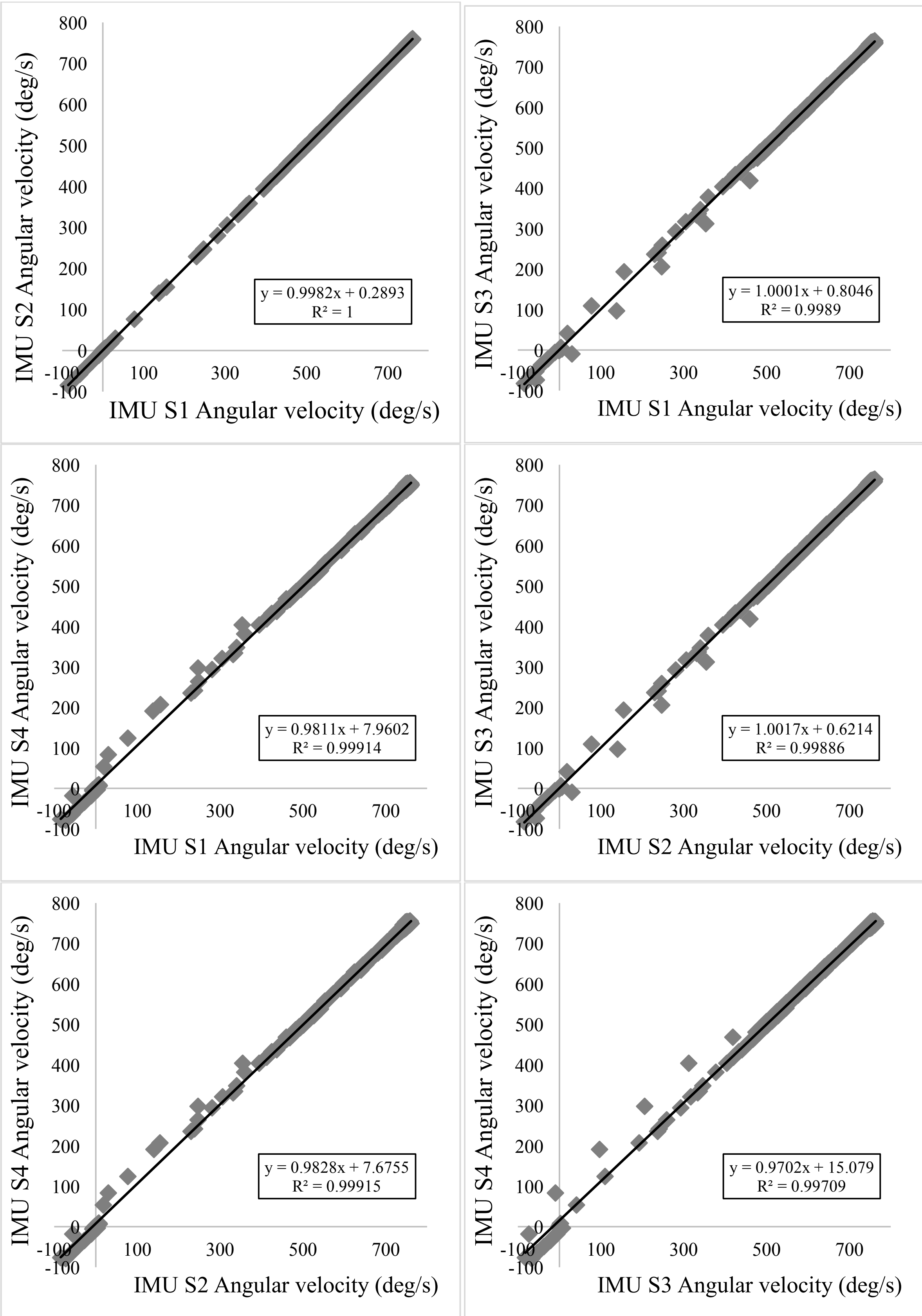
Note: Calibration refers to the mean linear regression equation applied to the raw IMU angular velocity data

Angular velocity visual comparison between IMU units



IMU	Mean difference of angular velocity curve	Correlation Coefficient (r)
S1 v S2	0.98 ± 0.34 (deg/s)	1.000
S1 v S3	2.32 ± 3.83 (deg/s)	0.999
S1 v S4	6.51 ± 4.84 (deg/s)	1.000
S2 v S3	2.77 ± 3.97 (deg/s)	0.999
S2 v S4	5.62 ± 4.83 (deg/s)	1.000
S3 v S4	7.64 ± 6.64 (deg/s)	0.999

Regression analysis between individual IMU sensors



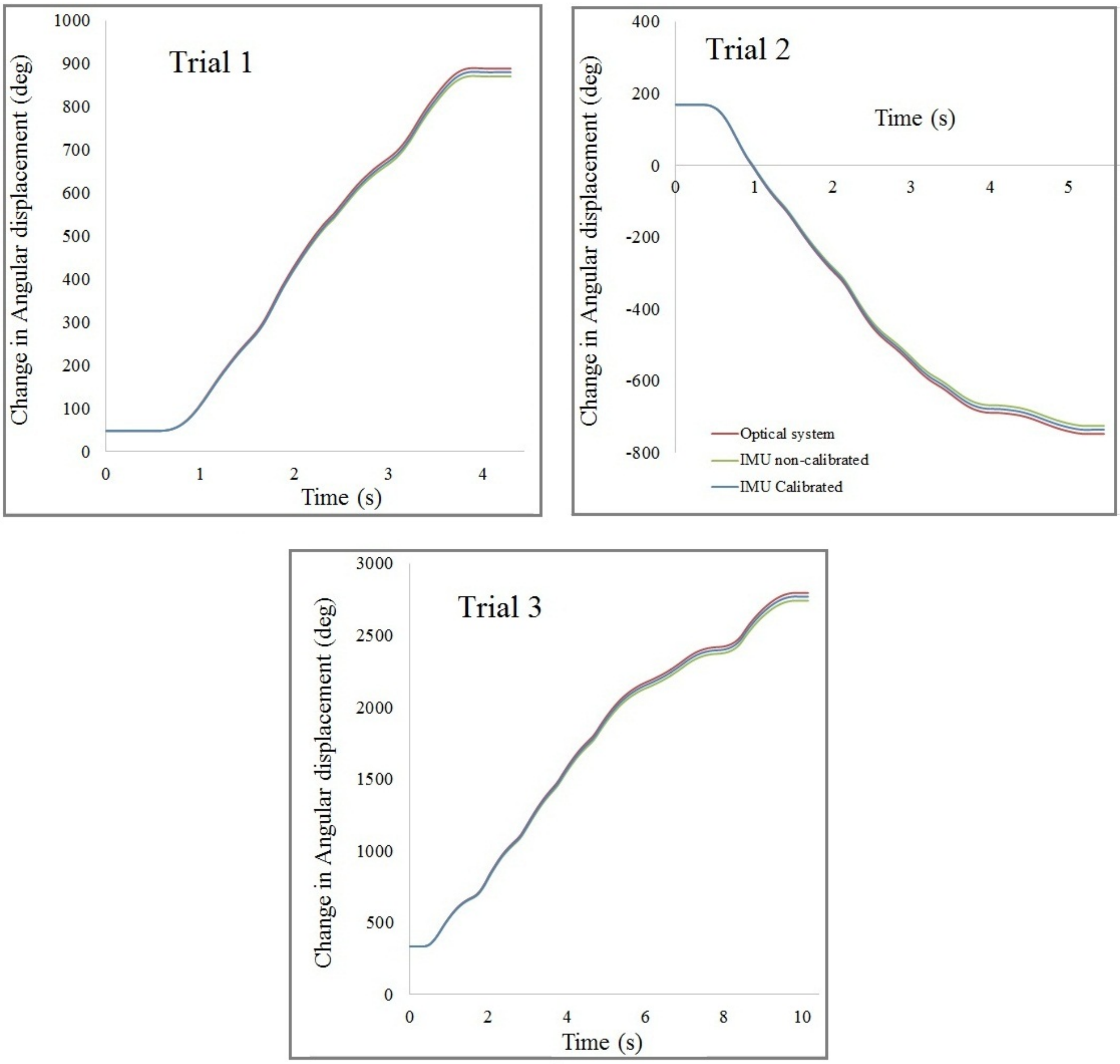
Validation of integration of IMU angular velocity to calculate the change in angular displacement

IMU	Trial	Duration of rotations (s)	Angular displacement: OTS system change (deg)	Angular displacement: **non-calibrated** IMU (deg)	Angular displacement: **calibrated** IMU (deg)	Percentage difference: **non-calibrated** IMU & OTS	Percentage difference: **calibrated** IMU & OTS
1	1	4.3	888.6°	870.3°	880.1°	2.10%	0.97%
	2	5.5	-748.7°	-726.2°	-737.2°	3.10%	1.57%
	3	10.1	2794.7°	2740.7°	2769.3°	1.97%	0.92%
2	1	4.3	888.6°	874.5°	884.3°	1.62%	0.49%
	2	5.5	-748.7°	-733.4°	-744.4°	2.09%	0.58%
	3	7.0	2324.6°	2291.9°	2315.2°	1.38%	0.36%
3	1	4.3	888.7°	870.3°	880.1°	2.10%	0.97%
	2	5.5	-748.8°	-726.2°	-737.2°	3.10%	1.57%
	3	11.0	2794.9°	2740.9°	2769.5°	1.96%	0.91%
4	1	4.3	888.6°	873.0°	882.8°	1.78%	0.66%
	2	5.5	-748.7°	-732.4°	-743.4°	2.22%	0.71%
	3	10.1	2794.7°	2749.7°	2778.4°	1.64%	0.59%
					Mean	**2.09%**	**0.86%**
					SD	**0.53**	**0.39**

Table notes: Calibration refers to the mean linear regression equation applied to the raw IMU angular velocity data
OTS = optical tracking system

Change in angular displacement visual comparison

Example: IMU 1



Note: Calibration refers to the mean linear regression equation applied to the raw IMU angular velocity data

Appendix 4

Two-dimensional video footage calibration

High speed Casio Exilim EX-FH100 cameras were used to record the movement patterns of springboard divers. For all investigations the cameras were placed perpendicular to the springboard of interest. Spirit levels from the cameras' fixed tripods were used to verify the perpendicular alignment of the axis of the camera with the floor. Each camera was set to high speed and shutter mode, with a frame rate of 120 Hz and a shutter speed of 1/250s.

Calibration

A customised calibration routine was developed for this current thesis' springboard diving investigations. An aluminium Frame, 3m tall by 7m wide, was constructed to calibrate cameras' fields of view. The calibration frame was placed level on the 1m springboard (Figure A). The frame extend 2.037m past the tip of the springboard, in order to calibrate the dive flight field of view. To assess whether the overhanging portion of the frame had any deviations from the horizontal plane a surveyor's optical level was used. There was a 0.023m deviation from the horizontal plane for the markers furthest from the tip of the springboard. To resolve this deviation, diagonal braces were added to the frame to strengthen and shift the weight towards the aspects of the frame supported by the level surface.

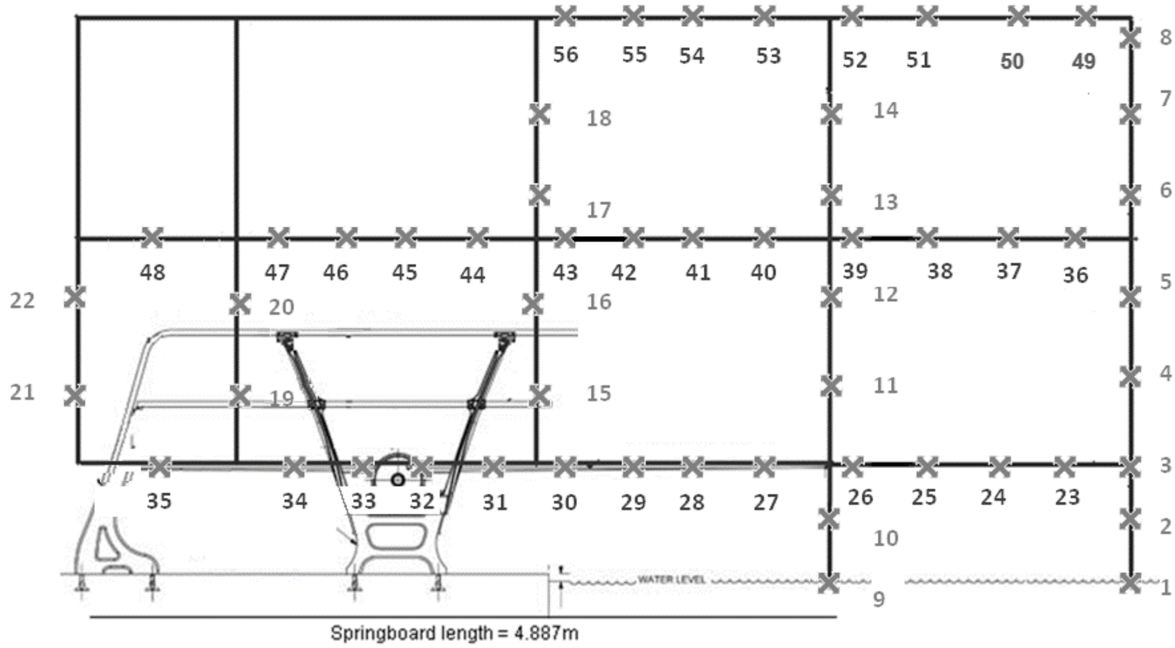


Figure A. Schematic representation of the calibration frame

Thirty two points on the calibration frame that were present in the cameras' field of view and were digitised over ten video frames using software Tracker (Brown, 2008). The mean of the ten digitised frames were then matched to their real world lengths in Excel (Microsoft Corp, Redmond, Washington, USA) and imported into a customised Matlab script (The MathWorks, Inc., Natick, MA, USA). The script was comprised of a standardised DLT function (Reinschmidt & Bogert, 1997), calibration coordinates equation (1) (Walton, 1981), and calculated error. Equation (1) is comprised of eight transformation parameters (h_1-h_8) equivalent to a homography matrix, where 1 is the ninth element. X and Y are the pixel coordinates and x, y are the corresponding real world coordinates (El-Ashmawy, 2015; Zhang, Zhang, & Zhang, 2003).

$$x = \frac{h_1 X + h_2 Y + h_3}{h_7 X + h_8 Y + 1}$$

$$y = \frac{h_4 X + h_5 Y + h_6}{h_7 X + h_8 Y + 1} \qquad (1)$$

The Matlab Script calculated error was defined as the difference between the calculated coordinates and the known real world displacements. The error measured was 0.004 ± 0.004

for both the x coordinates and 0.005 ± 0.003 for the y coordinates (Table A).

Table A. Example of the known displacements and calculated *x* and *y* coordinates, plus the error measure between the known and calculated *x* and *y*.

Point	**Real world *x* (m)**	**Real world *y* (m)**	**Calculated *x* (m)**	**Calculated *y* (m)**	**Error *x* (m)**	**Error *y* (m)**
2	6.870	0.482	6.854	0.487	0.016	0.005
4	6.870	1.485	6.869	1.489	0.001	0.004
6	6.870	2.484	6.866	2.494	0.004	0.010
8	6.870	3.480	6.867	3.487	0.003	0.007
12	4.833	1.995	4.833	1.996	0.000	0.001
14	4.833	2.989	4.832	2.995	0.001	0.006
24	5.870	1.012	5.875	1.002	0.005	0.010
28	3.870	1.012	3.871	1.014	0.001	0.002
30	2.870	1.012	2.869	1.014	0.001	0.002
32	1.870	1.012	1.872	1.012	0.002	0.000
34	0.870	1.012	0.869	1.015	0.001	0.003
37	5.870	2.272	5.875	2.268	0.005	0.004
41	3.870	2.272	3.862	2.278	0.008	0.006
50	5.870	3.540	5.877	3.529	0.007	0.011
54	3.870	3.540	3.869	3.535	0.001	0.005

Table notes: Point refers to the marker number on the calibration frame shown in figure A.

Calibrating the field of view for the 3m springboards – linear scaling

Due to the height and position of the 3m springboards at the Sydney Olympic Park Aquatic Centre the calibration frame was unable to safely be placed level with the springboard of interest, therefore a linear scaling method was adopted. A pilot test was conducted to assess the effect of camera zoom and lens distortion. Makers with known displacements were placed on a solid wall (Figure B). A video camera was set level and perpendicular to the centre marker and set to the same settings as the aquatic environment, 120 Hz with a shutter speed of 1/250s. The markers were recorded for 10-15s at eight different zoom levels, ranging from 0mm-66mm. An average of five digitised frames per coordinate were collected. Two-dimensional DLT parameters were calculated for the 0mm camera zoom. These DLT parameters were placed into equation (1) for each of the remaining seven incremental increases in zoom, and calculated coordinates were produced. In order to scale the different camera zooms to the real world measures linear regressions were performed against the know displacements. An example of the linear regression is shown in Figure C for the 48mm camera zoom.

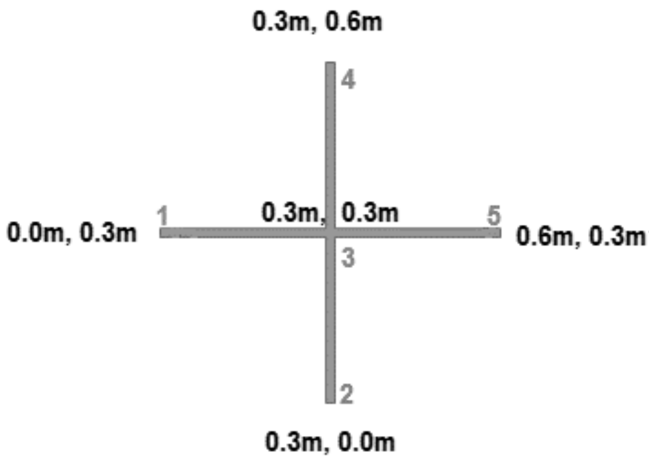


Figure B. Schematic representation of the known displacements layout.

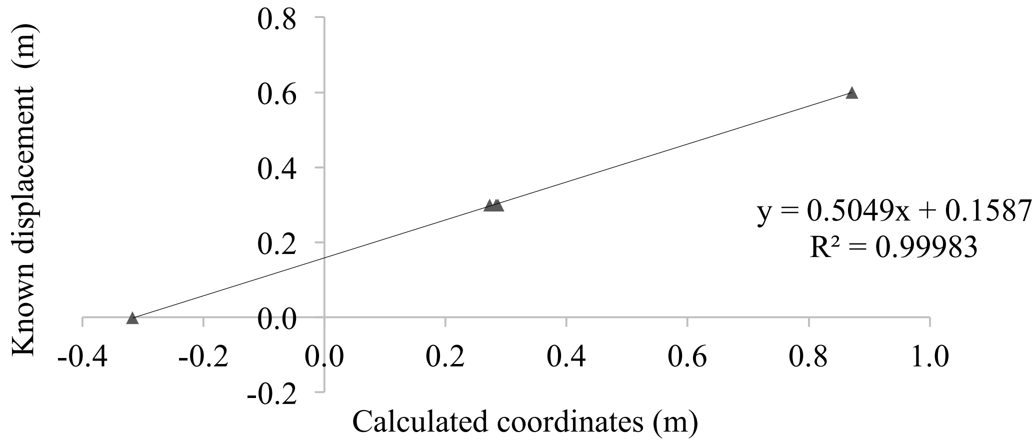


Figure C. Example of the linear regression conducted with the known displacements represent in: Figure B and the calculated coordinates for the 48mm camera zoom.

The regression equations produced at each zoom level were used to scale equation (1). The scaling of the *x* calculated coordinates is represented in equation (2).

$$x_{scaled} = \left(\frac{h_1X + h_2Y + h_3}{h_7X + h_8Y + 1}\right) * a + b_x \quad (2)$$

Where a and b_x are taken from the linear regression equation.

Additional steps were needed to be taken to scale the calculated coordinates for the *y* axis, due to only having one known height aquatic environment, the 3m springboard. The *y* scaled calculated coordinates are presented in equation (3).

$$y_{1-5} = \frac{h_4X + h_5Y + h_6}{h_7X + h_8Y + 1} * a + b_y$$

Where y_1-y_5 are the *y* axis calculated coordinates for each of the five known markers in Figure B.

$$y_{1-5\,(mean)} = \frac{y_1 + y_2 + y_3 + y_4 + y_5}{5}$$

$$b_{yi} = 0.3 - y_{scaled\,(mean)}$$

Where 0.3 is equal to the mean of the known y axis displacements of y_1-y_5 in Figure B.

(3)

$$y_{scaled} = \frac{h_4X + h_5Y + h_6}{h_7X + h_8Y + 1} * a + b_{yi}$$

The error between the linear regression scaling method and real world coordinates ranged between 0.000-0.004m in both the *x* and *y* axis (Table B). With the maximum scaling error of 0.004m equating to only 1% difference with the known displacements, we were confident that there was no camera lens distortion as the camera zoom changed. Therefore we were confident in adopting this scaling method to the 3m springboard camera set up in the aquatic environment.

Table B. Example of the application of the linear regression scaling method at zoom 48mm. The regression scaled the DLT parameters to best fit the real world coordinates

Regression	Point	Real world (m)		DLT (m)		Scaled (m)		Error (m)	
		X	Y	X	Y	X	Y	X	Y
Mod_x = DLTx* 0.5049 + 0.1587	1	0.000	0.300	-0.317	0.311	-0.001	0.298	0.001	0.002
	2	0.300	0.000	0.284	-0.282	0.302	-0.002	-0.002	0.002
Mod_y= DLT_y* 0.5049 + 0.1409	3	0.300	0.300	0.287	0.317	0.304	0.301	-0.004	-0.001
	4	0.300	0.600	0.274	0.904	0.297	0.597	0.003	0.003
	5	0.600	0.300	0.871	0.318	0.599	0.301	0.001	-0.001

The chosen 3m springboard acted as its own linear reference with 0.4m increment markers along the *x* axis; 0.000m, 0.400m, 0.800m, 1.200m, 1.600m and a known height of 3.000m. Five video frames from each *x* axis increment were digitised. The mean of each increment was then calculated. DLT parameters and calculated coordinates were determine using the calibration routine for the 1m springboard. A linear regression was then conducted between the calculated coordinates and the known x axis displacements (example shown in Figure D), following the same method as the camera zoom pilot test. Equation (2) was used to determine the scaled x axis calculated coordinates, whereas the y axis was slightly modified. The original *byi* (3) was equivalent to the of the known y axis displacements in Figure B (0.300m). The mean of the known y displacement for the 3m springboard calibration was 3.000m, equation (4).

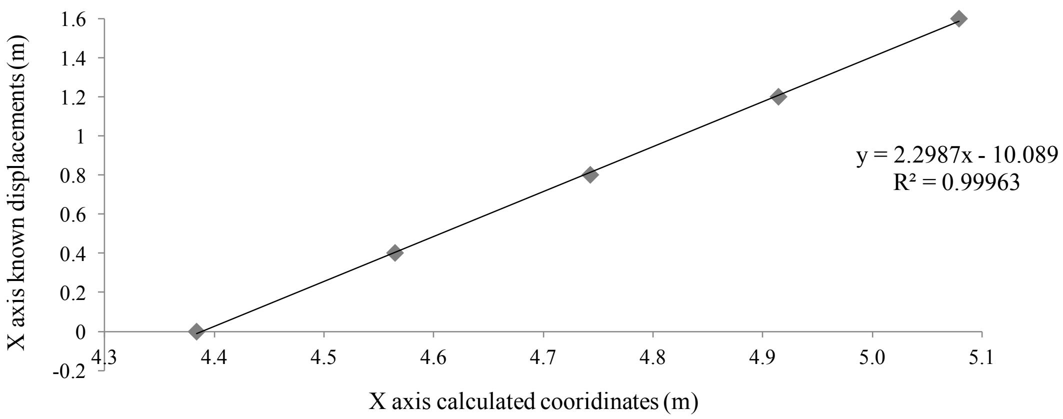


Figure D. An example of the linear regression performed to calibrate the field of view from one subjects 3m springboard session.

$$3m\ springboard\ y_{1-5\ (mean)} = \frac{y_1 + y_2 + y_3 + y_4 + y_5}{5}$$

$$b_{yii} = 3.0 - 3m\ springboard\ y_{1-5(mean)}$$

Where 3.0 is equal to the average of the known y axis displacements for the 3m springboard.

(4)

$$y_{3m\ springboard\ scaled} = \frac{h_4X + h_5Y + h_6}{h_7X + h_8Y + 1} * a + b_{yii}$$

The mean difference between the scaled and real world coordinates for the calibration routine conducted for the 3m springboard was 0.005±0.005m for x and 0.006±0.005m for y, with an overall range across the multiple data collection session equating to 0.000-0.023m for both the x and y coordinates (Example shown in Table C).

Table C. An Example of the real world, calculated and modified X and Y coordinates, plus the error at X and Y. Example coordinates have been taken from the regression equation in Figure 2.

Real world X (m)	Real world Y (m)	Calculated X (m)	Calculated Y (m)	Modified X (m)	Modified Y (m)	Error X (m)	Error Y (m)
0.000	3.000	4.384	1.386	-0.011	2.977	-0.011	-0.023
0.400	3.000	4.565	1.393	0.404	2.992	0.004	-0.008
0.800	3.000	4.743	1.397	0.814	3.001	0.014	0.001
1.200	3.000	4.914	1.400	1.208	3.009	0.008	0.009
1.600	3.000	5.079	1.406	1.586	3.021	-0.014	0.021

Appendix 5

Intra-operator digitisation and time identification reliability

One video was randomly selected from the current thesis data base. The video represented the footage collected for the dive flight investigations from the 3m springboard. The video was digitised once a week, over a five week period, in order to determine the operator reliability. The video was calibrated using the customised calibration routine. Eleven kinematic variables were calculated (Table D). Mean, range and standard deviations were calculated to determine the intra-operator digitising reliability. Standard deviation was used an indication of the Typical error (Hopkins, 2000a).

The intra-operator digitising typical error was small (Table E). Maximum depression and dive distance measures were reproducible within millimetres. Dive height showed a greater typical error with a maximum of 0.012m. The difference in height may have been caused by takeoff frame identification. One frame difference, for example, resulted in a 0.056m height different for the vertical position of the iliac crest at takeoff. As true takeoff may actually be in between the two selected frame numbers chosen in the intra-operator reliability, we can conclude that the error is acceptable. Time measurements typical error represented a difference of 1 video frame. Therefore the operator accuracy for the time measures was 1/120 fps. Takeoff, somersault and entry angles intra-operator typical error was no greater than 1.6°.

Table D. Kinematic variables calculated via high speed video footage.

Kinematic Variable	***Calculation***
Maximum depression	Maximum downward vertical distance the springboard travel Max. Dep. = $SB_{rest} - SB_{Max.Dep}$
Takeoff hip angle	Relative angle between the lower limb and trunk segment at takeoff
Takeoff body angle	Defined from the line between the ankle and iliac crest with respect to the right hand horizontal at the final frame where the foot was in contact with the springboard
Initial Flight duration	Duration of the time from takeoff to the first frame where the diver's hands touched their legs to form the somersault position
Somersault duration	Duration of the time taken from the somersault position to the first frame where the diver's hands leave their legs to begin the somersault deceleration process.
Opening duration	Duration of the time taken from the somersault open to the first frame where the diver's hands break the water.
Total Flight duration	Duration from the final frame of foot contact with the springboard to the first frame where hands broke the water on entry (Sanders and Gibson 2000).
Dive height	Peak height of the diver's iliac crest. Calculated as the vertical difference between the iliac crest at peak height and the iliac crest at takeoff
Dive distance	The linear distance travelled by the diver with respect to the end of the springboard.
Entry hip angle	Defined from the line between the lateral malleolus and greater tubercle of the humerus with respect to the right hand horizontal at the first frame the hands broke the water (Sanders & Gibson, 2000)
Entry body angle	Relative angle between the lower limb and trunk segment at the first frame the hands broke the water

Table E. Kinematic variables mean, maximum, minimum and typical error (SD)

Kinematic Variable	Mean	Max	Min	SD
Maximum depression	0.881m	0.883m	0.879m	0.002m
Takeoff body angle	72.7°	73.0°	72.2°	0.3°
Takeoff hip angle	81.7°	83.2	80.5°	1.2°
Initial flight duration	0.24s	0.25s	0.23s	0.01s
Somersault duration	0.93s	0.95s	0.92s	0.01s
Opening duration	0.22s	0.23s	0.20s	0.01s
Total time of flight	1.38s	1.38s	1.38s	0.00s
Dive height	1.142m	1.159m	1.127m	0.012m
Dive distance	2.316m	2.321m	2.311m	0.004m
Entry body angle	115.2°	116.66°	113.5°	1.2°
Entry hip angle	116.5°	119.1°	114.5°	1.6°

Appendix 6
Conference presentations during PhD candidature

2014 International Society of Biomechanics in Sports Conference Proceedings.
Johnson City, Tennessee, USA

A COMPARISON OF MULTIPLE FORWARD SOMERSAULT DIVES FROM THE 3M SPRINGBOARD: A CASE STUDY

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The aim of this study was to examine the differences in the angular velocity profiles and key positional angles of multiple forward somersault dives from the 3m springboard. One internationally ranked male diver performed the forward 1½, 2½, 3½ pike (P) dives while a second diver performed the 4½ tuck (T) dive. High speed video footage and inertial measurement units (IMU) were used to determine eight biomechanical variables. Results indicate that the diver performing the 4½T had a 177 deg/s increase in the angular velocity plateau and held onto his somersault position for 0.26s longer when compared to the 3½P. The forward 4½T takeoff angles were similar to those used in the 2½P and 3½P, but were slightly under rotated at entry. The IMUs proved to be a suitable analysis tool for springboard diving coaches wanting 'quick turnaround' performance analysis.

KEY WORDS: Angular velocity, inertial measurement unit, 109C

INTRODUCTION: During the 2012 London Olympics nine out of twelve divers competing in the men's 3m springboard final performed the forward 4½ tuck somersault dive, (i.e.,109C, 4½T) compared to no divers attempting this dive at the 2008 Beijing Olympics. The turning point came in 2009, when FINA made a significant rule change enhancing the degree of difficulty score for more difficult dives (Noth & Kothe, 2013). With higher scores to be gained, there is now an increased reward from attempting to perform more somersault rotations. As a consequence, all of the podium winners at the London Olympics and the 2013 World Championships performed the 4½T.

Limited analysis techniques have been available for measuring biomechanical variables of springboard divers. Formerly the most common data analysis procedure has been to video record athletes and analyse the footage with 2D digitisation (Sanders & Wilson, 1988; Sanders & Gibson, 2000; Walker, Sinclair, & Rickards, 2013). This procedure is time consuming and operator measurement consistency problems are present in non-marker conditions, such as competition (Bartlett, Bussey, & Flyger, 2006).

To address these limitations and better understand how dive degree of difficulty can be developed, the current case study aimed to examine the different angular velocity profiles and key positional angles of the forward 1½ pike dive (103B, 1½P), the forward 2½ pike dive (105B, 2½P), forward 3½ pike dive, (107B, 3½P) and 4½T from the 3m springboard. Furthermore the current study endeavoured to determine the biomechanical application of inertial measurement units (IMU) to the sport of springboard diving and what feedback possibilities these produce for coaches and their athletes.

METHOD: One internationally ranked male diver (height = 1.74m, weight = 73.2kg) from the New South Wales Institute of Sport, (NSWIS) who regularly performs the 1½P, 2½P & 3½P dives was recruited. This athlete was not currently able to perform the 4½T. Therefore, to determine what is required to perform the 4½T, another male diver (height = 1.60m, weight =61.0kg) attending an international training camp in Sydney, Australia was also recruited.

An inertial measurement unit, IMU, (IMeasureU, Ltd; Auckland, New Zealand) was used to measure angular velocity profiles. The IMUs are 22 mm x 34 mm x 10 mm in size and have a mass of approximately 12g (Finch, Lintern, Taberner, & Nielsen, 2011). They are hermetically sealed allowing for use in water environments. IMUs were used to calculate peak angular velocity, average angular velocity plateau, the difference between the peak and plateau angular velocity and angular velocity plateau duration. The angular velocity plateau was determined by an iterative procedure that identified the portion of the graph where the angular velocity was >95% of the plateau mean.

In additional to the IMU's, a high-speed Casio Exilim EX-FH20 camera was placed level with and perpendicular to the 3m springboard. The camera was set to 120fps, with a shutter speed of 1/250s. The field of view was limited to the divers' last step on the springboard, hurdle, dive, and dive entry. Video was digitised using Tracker software (Brown, 2008). A calibration frame, 7mX3m, (Sinclair, Walker & Rickards, 2012) was used to transform digitised coordinates into real world coordinates. The takeoff and entry angles were calculated from the digitised coordinates. Takeoff angle was defined as from the line between the ankle and iliac crest with respect to the right hand horizontal. Entry angle was defined from the line between the iliac crest and the shoulder with respect to the right hand horizontal. Relative hip angles, defined as the angle between the thigh and trunk segments, were also calculated at takeoff and entry. Total time of flight was calculated and was measured from the final frame of foot contact with the springboard to the first frame where hands broke the water on entry (Sanders and Gibson 2000).

Testing sessions were conducted during the divers' scheduled training at the Sydney Olympic Park Aquatic Centre. Divers were asked to perform their regular dry land warm up routine. IMUs were then strapped to the divers' lower back (L4/L5) using a transparent film dressing (Opsite Flexigrid). The NSWIS diver performed five repetitions of the 1½P, 2½P & 3½P and the international diver performed the three repetitions of the 4½T. A 95% Confidence Interval of the true mean (CI) was used to assess difference in rotational velocity, angle and time measures between each dive type.

RESULTS AND DISCUSSION: There was a common trend in angular velocity profile for each dive, Figure 1. The negative velocity seen at the beginning of 4½T rotation velocity profile represents the vigorous extension of the lower limbs to maximally depress the springboard. During takeoff preparation, the diver begins to lean forward to generate the angular momentum required for the dive (Sanders & Gibson, 2000). This is represented by the positive increase in angular velocity. There is a slight plateau in angular velocity at takeoff. When leaving the springboard, the diver begins to adopt the tight somersault position. At approximately 75% of the first somersault, the diver lost his tight tuck position represented by deceleration at the 1.08s mark, Figure 1. The diver then 'pulled' back into the tight somersault position with an average plateau angular velocity and duration of 1095±3deg/s and 0.91±0.01s respectively. The diver released from this position to decelerate their rotation in preparation for water entry.

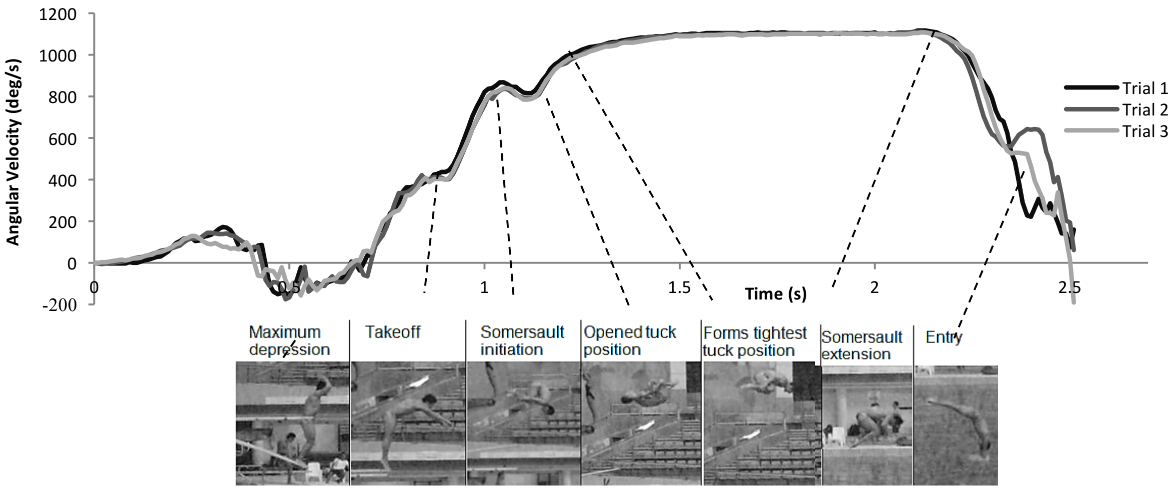

Figure 1: IMU Angular velocity profile of the 4½T dive - an example from one athlete.

When comparing differences between 1½P, 2½P, 3½P & 4½T, there were obvious changes in angular velocity profile as well as changes in the positional angles and time measures (see Table 1 & Figure 2). The 1½P, 3½P & 4½T show a smooth angular velocity plateau followed by deceleration, represented by the release of the somersault position. However, the 2½P displays shorter plateau duration prior to somersault position release. One would have expected that the 1½P would have the shortest plateau duration, but this is a dive used in competition with the aim of demonstrating smooth and flowing movements. On the other hand, the 2½P is used only as a build up for the 3½P. Coaches want to see fast rotation at the 'top of the dive' in order to progress to the 3½P. Thus, the diver forms a tight pike to learn the position for the 3½P, but then needs to 'open out' earlier from the pike to ensure water entry is at the vertical position and with no over rotation.

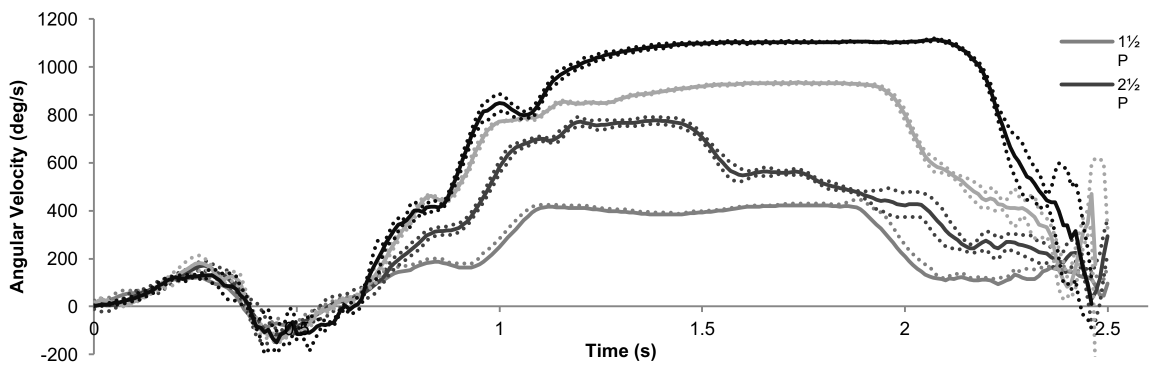

Figure 2: Angular velocity profile of the 1½P, 2½P, 3½P & 4½T. The solid line represents the mean and dotted line represents 95% CI.

	1½P	2½P	3½P	4½T
Peak velocity (deg/s)	443± 16	781 ± 15	934 ± 4	1113 ± 6
Average velocity plateau (deg/s)	407 ± 4	764 ± 15	918 ± 4	1095 ± 3
Plateau duration (s)	0.83 ± 0.04	0.32 ± 0.03	0.65 ± 0.01	0.91 ± 0.01
Peak & plateau difference (deg/s)	36 ± 16	16 ± 3	16 ± 1	19 ± 2
Takeoff angle (deg)	84.6. ± 0.2	83.5 ± 0.8	81.5 ± 0.7	81.8 ± 2.9
Takeoff - hip angle (deg)	148.3 ± 4.7	117.8 ± 5.6	87.1 ± 2.7	117.3 ± 12.9
Entry angle (deg)	103.2 ± 2.5	112.0 ± 5.0	113.9 ± 4.2	118.5 ± 8.1
Entry - hip angle (deg)	175.2 ± 3.2	168.1 ± 4.0	164.7 ±3.9	135.0 ± 6.4
Time of flight (s)	1.61 ± 0.01	1.55 ± 0.01	1.49 ± 0.01	1.59 ± 0.01

Table 1: Comparison of the increasing degree of difficulty dives, represented by the mean and 95% CI. Diver 1 performed 1½P, 2½P & 3½P and Diver 2 performed 4½T

There was an increase of 177deg/s during the angular velocity plateau from 3½P to 4½T, which coincides with the report that maximum centripetal force is increased by ~2BW from 3½P to 4½T (Miller, 2013). The somersault position during the 4½T angular velocity plateau was also held for an additional 0.26s. Therefore, physically divers must be strong enough to hold onto the tight somersault position, in order to increase their degree of difficulty.
As rotational requirements increase for more difficult dives, a diver must create a larger moment arm for the springboard reaction force to develop the required angular momentum. The moment arm is created by forward body lean during takeoff. The springboard will apply a horizontal reaction force to the diver's feet, producing a torque, rotating the diver forward (Sanders & Gibson, 2000). This data shows there was an increase in the forward lean at takeoff from 1½P-3½P, which came at the expense of height as can be seen from the decreased flight time (Miller & Sprigings 2001; Sanders & Wilson, 1988).
The data shows no change in takeoff angle of lean from the 3½P to 4½T, however there was a change in the relative hip angle. The diver performing the 4½T had less flexion about the hip. It has been reported that divers are able to maintain a more vertical body position at takeoff when performing a dive in the tuck position, resulting in less absorption of the elastic strain energy from the springboard during the maximum depression recoil. Therefore, vertical velocity is greater than that of the same dive performed in pike (Miller & Sprigings, 2001). The diver performing the 4½T was able to gain additional height in the dive, which is shown by 0.10s increase in average time of flight; providing more 'air time' to perform the additional somersault revolution.
As a diver increases their degree of difficulty, they run the risk of missing the perfect entry and being subsequently awarded a lower score. Entry angles in the current study would result in perfectly vertical body position of 90°, with an extended hip of 180°. There was a slight difference of 4.7° in the entry angle and a substantial difference of 31.2° in the relative hip angle from the 3½P to the 4½. Thus, the diver performing 4½T entered the water in an under rotated position, which may result in points being deducted in a competition scenario.
The current case study provides an initial understanding of the differences in the 3½P and 4½T. A limitation of the study is that the NSWIS diver specialises in the platform event, whereas the international diver specialises in the springboard event. There are different training principles for the disciplines with springboard athletes highly focusing on lower limb strength, in order to establish more energy into the spring system. Therefore, physically, the international diver is more developed to perform the 4½T.
IMUs are an advantageous tool for measuring the biomechanics of diving. They clearly measured the divers' angular velocity profiles during multiple somersault dives, providing initial information for the differences in multiple somersault dives. They significantly reduced data analysis time, enabling a quicker data turnaround. This makes IMU's ideal for providing training and competition performance analysis, and for coaches to informatively assist their athletes.

CONCLUSION: The 'air time' a diver has to perform additional somersault rotations is of key importance in order to execute a dive with a perfect entry position. A diver wanting to perform the 4½T must have a combination of mechanical (i.e. takeoff hip angles & angular velocity) and physical (i.e. strength) elements to provide them with adequate time of flight. If a diver does not reach the required level of these elements they are at risk of entering the water under rotated and therefore loosing points from the judges.

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VARIABILITY AND THE CONTROL OF ROTATION DURING SPRINGBOARD DIVING

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This study explored the variability in angular velocity profiles across multiple somersault dives. Four international level divers performed 4-6 repeated dives of either 3½ somersaults with pike, or 4½ with tuck, from a 3 m springboard. An inertial measurement unit (IMU) was attached to the lower back to record angular velocity during all trials. Each diver produced highly consistent patterns of dive time duration and angular velocity, with standard deviations less than 1% of the mean. No consistent pattern of correlation between velocity and duration of the held tuck/pike position was apparent, and no other evidence of mid-dive feedback control was evident from the present methodology. This may be the result of performing dives with a high degree of difficulty, providing little time for movement adjustments during 'kick out' to affect water-entry.

KEY WORDS: springboard diving, variability, control, angular velocity.

INTRODUCTION: Dynamical systems theory suggests that a property of highly skilled movement is the capability to functionally control and introduce degrees of variability according to task requirements (Handford et al., 1997). However, whilst skilled performance often requires a high consistency of movement outcomes (low outcome variability), skilled performers will often exhibit a higher intra-limb variability to achieve these consistent outcomes (high coordination variability) (Wilson et al., 2008).

In the context of diving, O'Meara (2010) has previously showed high levels of consistency in terms of angular velocity patterns when elite divers performed forward tuck somersaults from the floor during dry land training. Specifically, coefficients of variation in average angular velocity ranged between 0.6-1.7%. Similar findings have also recently found in somersaults performed from a springboard (Walker et al., 2014). While it is difficult to directly compare measures of variability between different variables and in different performance contexts, coefficients of variation for other skilled performances have reported higher values; such as 5% for the last stride length of a long jump run-up (Galloway & Connor, 1999) or 7% for flight time of a standing somersault (Gittoes et al., 2011).

During a somersault dive, divers leave the springboard with a given amount of angular momentum and maintain a constant momentum until water entry (Sanders & Wilson, 1987). When performing dives that include multiple somersaults, divers maintain a tight tuck or pike position to reduce their moment of inertia, and therefore to assist rotational speed, before 'kicking-out' (i.e., increasing their mass moment of inertia and reducing the velocity of rotation). The diver then aims to achieve an extended and vertical position at the point of water entry with minimum splash. Therefore, being able to coordinate, control, and adjust movement presents a substantial challenge for divers. Understanding and identifying the process by which it can be achieved has important implications, least of all for coaching and performance optimisation.

This study firstly explored the degree of variability in angular velocity profiles across multiple somersault dive attempts. Secondly, it examined whether divers actively controlled the timing of the 'kick out' in accordance with variations in the velocity of rotation in an effort to assure accurate and reliable water entry.

METHODS: Four international level divers participated in this study. Each completed 4-6 forward somersault dives at their highest degree of difficulty from a three metre springboard. Two divers (D1, D2) performed the three and a half somersault dive in a pike position (3½P), and two (D3, D4) performed the four and a half somersault dive in a tuck position (4½T).

Angular velocity was measured using a waterproof inertial measurement unit (IMU) (IMeasureU, Ltd; Auckland, New Zealand) with embedded gyroscope, strapped to the lower back (at L4/L5) using a transparent film dressing (Opsite Flexigrid). Figure 1 illustrates a typical angular velocity profile from a 4½T dive. The initial negative velocity coincided with divers extending their body during board depression. Take-off time and departure from the springboard could not be accurately determined from the angular velocity trace, so dive time was counted from the point of maximum negative velocity through to water entry. Profiles for each diver displayed an initial velocity peak at the approximate point of completing half a rotation (Time 1.2 s, Figure 1). This point was used to define the start of a plateau region, where velocity remained relatively constant while divers held their full tuck/pike positions. An iterative procedure was then used to identify the plateau end point; when angular velocity dropped below the average velocity across the plateau. Angular displacement was calculated by numerical integration of the angular velocity across time. Within subject correlations were performed between selected kinematic variables to identify possible feedback mechanisms utilised by each diver.

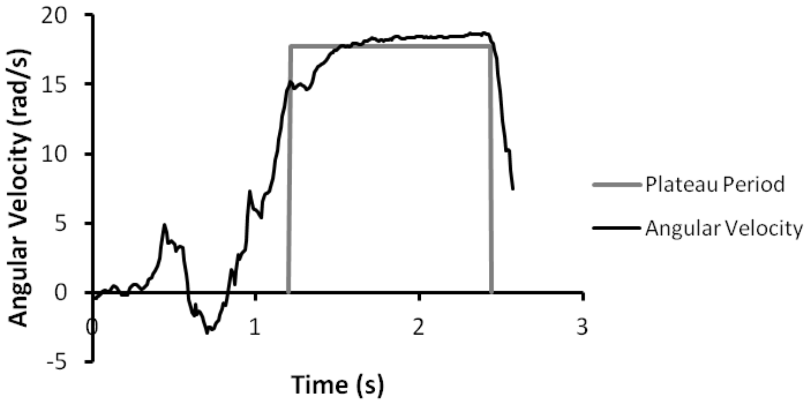

Figure 1: Angular velocity for one exemplar trial (4½T) illustrating calculation of the plateau region.

RESULTS AND DISCUSSION: Each diver produced a consistent pattern of performance, with high similarity between divers performing the same respective dive type (see Figure 2). Total dive time was consistent with standard deviations < 1.1% of total dive time (see Table 1). All participants displayed low variability between trials in angular velocity (0.5 - 1.0%), and in plateau duration time (1.5 - 2.3%). All participants except D4 produced less variability between trials in their angular velocity measures (1%) than they did for variability in the plateau duration (1.5 - 2.3%).

Between 70 and 83% of the total rotation for each dive was produced during the plateau region where divers held a fixed tuck/pike position. Consistency during this portion of the dive is therefore very important if divers are to achieve the required amount of rotation to enter the water in a reasonably upright position. This high degree of consistency between dives is a necessary requirement to land a dive safely and with minimal splash. During the plateau, all divers rotated between 8-10° every 0.01s. Consequently, changing the plateau velocity or duration by only 1% would change the amount of rotation between 9-13°, depending on the divers' velocity and duration.

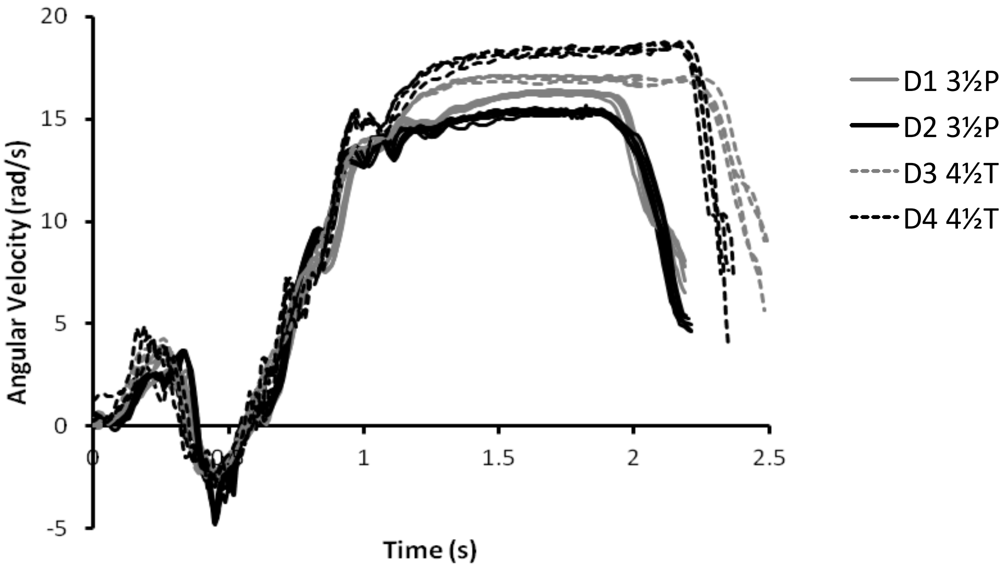

Figure 2: Angular velocity profiles for all trials of each participant (D1 – D4).

Table 1: Mean and coefficient of variation for all kinematic measures and selected correlations. Data represent the mean of all trials completed by each diver, D1-D4.

	D1 3½P (n=5)	D2 3½P (n=6)	D3 4½T (n=4)	D4 4½T (n=4)
Duration of dive (s)	1.74 ± 0.6%	1.75 ± 0.6%	2.03 ± 0.4%	1.90 ± 1.1%
Duration of plateau (s)	0.97 ± 1.8%	0.94 ± 1.5%	1.26 ± 2.3%	1.25 ± 1.5%
Velocity of plateau (° s^{-1})	888 ± 0.5%	844 ± 0.7%	944 ± 0.6%	1009 ± 1.0%
Rotation before plateau (°)	156 ± 2.5%	154 ± 3.3%	186 ± 1.0%	160 ± 3.1%
Rotation during plateau (°)	855 ± 0.9%	796 ± 1.3%	1202 ± 2.8%	1267 ± 1.6%
Rotation after plateau (°)	148 ± 7.6%	191 ± 3.7%	160 ± 13.1%	103 ± 10.8%
Total rotation (°)	1160 ± 0.7%	1141 ± 0.7%	1548 ± 1.0%	1530 ± 1.2%
Correlation between the amount of rotation and the duration of plateau	+0.83*	+0.87**	+0.99**	+0.82*
Correlation between the amount of rotation and the velocity of plateau	$+0.63^{ns}$	-0.14^{ns}	$+0.70^{ns}$	$+0.45^{ns}$
Correlation between the velocity of rotation and the duration of plateau	$+0.63^{ns}$	-0.53^{ns}	$+0.58^{ns}$	-0.14^{ns}
Correlation between the rotation before opening out and rotation after opening out	-0.72^{ns}	-0.87**	-0.92*	-0.57^{ns}

* Correlation is significant (pℂ0.05). ** Correlation is significant (pℂ0.01). ns indicates correlation is not significant (p>0.05).

There was relatively low variability in total rotation ($\overline{X}$=0.9%) compared with the amount of variability before the plateau ($\overline{X}$=2.5%), during the plateau ($\overline{X}$=1.7%) or after the plateau ($\overline{X}$=8.8%). The total rotation represents low outcome variability, as would be expected for experienced performers. The individual component rotations, while not exactly the same concept as the coordination variability between segments described by Wilson et al. (2008), is consistent with this theory as the skilled performers are able to link these more variable component rotations together to produce a consistent total rotation before water entry.

A strong correlation was evident for all divers between plateau duration and the amount of rotation during this period (+0.88 ± 0.08). Correlations between the amount of rotation and angular velocity were comparatively weaker (+0.41 ± 0.38), suggesting that tuck duration had a greater association with the amount of rotation achieved. If divers were modulating the duration of their plateau region to achieve a consistent amount of rotation we would have expected a negative correlation between rotation velocity and plateau duration. There is no evidence that divers did this; however, with only one diver showing a moderate negative correlation between velocity and duration of plateau. Indeed, two participants demonstrated a positive correlation, where the faster rotations also had a longer duration of the plateau.

Negative correlations were found for all divers (-0.77 ± 0.16) between the amount of rotation occurring before the end of the plateau and the amount of rotation after the plateau. Part of this effect would occur largely because, if divers held the tuck longer, producing more rotation during the plateau, then there would be less time available for rotations to occur after the plateau.

Perhaps athletes control the rate they open out after the plateau in order to control water entry. While Figure 2 demonstrates there were differences between divers in the rate of velocity decline after the plateau, there was no apparent pattern to the variation between dives. For example, participant D3 performed two dives where the velocity decline was more rapid than the other two; however, those were not dives where more rotation had occurred before the end of the plateau. Further consideration will need to be given to methods for quantifying movement control during the opening out portion of a dive. Such methods will likely need to consider changes in shape of the velocity profile after the plateau, not simply the average slope of the curve.

The 3½P and 4½T dives investigated in this study were of the highest degree of difficulty able to be performed by these particular divers. Perhaps the divers were merely trying as hard as they could to complete the required number of revolutions, and had no spare capacity to controllably adjust their position for entry. Further research will use more trials and consider dives with lower numbers of rotations to see how body position is controlled prior to entry.

CONCLUSION: A high degree of consistency in angular velocity appears necessary when performing multiple somersaults as part of a successful dive. Divers may have regulated the duration and velocity of their somersaults to within 1% of variability because to do otherwise would have resulted in a ten degree change in total rotation for the dive. There is no explicit evidence to suggest that divers were able to intentionally manipulate the timing of ‘opening-out’ from a tuck/pike position in response to variations in velocity of rotation. Thus, we remain reserved in understanding and recommending whether and how diving movements can be controlled prior to water entry. To progress from this position, it is proposed that examining dives with a lower number of required rotations, and consequently with a lower degree of difficulty, may provide better insight as to whether highly skilled divers can controllably modify their angular velocity in mid-flight to affect the angle of water entry.

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A KINEMATIC ANALYSIS OF THE BACKWARD 2.5 SOMERSAULTS WITH 1.5 TWISTS DIVE (5253B) FROM THE 3M SPRINGBOARD

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The aim of this case study was to determine the practical application of 3D inertial measurement units and compare angular velocity profiles, key position angles and event timings for the backward 2½ somersaults with 1½ twists (5253B). One male diver performed 11 trials of the 5253B while 3D inertial measurement units (IMU) and high speed video were used to measure kinematic variables. Peak angular velocity about the somersault and twist axes were 900±11deg/s and -1435±28.deg/s, with highly consistent patterns displayed for total flight time (<1%) and peak angular velocity (≤2%). A comparison between the 5253B and the backward 2½ somersaults dive (205B) indicated significant kinematic differences at take-off, flight and entry. IMU provide a quick and practical analysis tool for coaches wanting to monitor their athlete's daily performance.

KEYWORDS: variability, angular velocity, inertial measurement unit, 205B

INTRODUCTION: A straight somersaulting dive only requires rotational control about one axis of movement. A twisting dive increases the complexity of the aerial movement as it requires rotational control about multiple axes (Yeadon, 2001). During the twist portion of a somersault, a straight body alignment must be attained to minimise the moment of inertia about the longitudinal axis. This will allow the twist to be completed quickly, and subsequently slowing the somersault rotations about the transverse axis (Sanders & Burnett, 2007). The backward 2.5 somersaults with 1.5 twists (5253B) is a high demanding dive which requires the generation of a large angular momentum during a standing takeoff from the 3m springboard. Due to its high demand and complexity, FINA increased the degree of difficulty rating from 3.3 to 3.4 in 2014, increasing the incentive for divers to perform this dive.

In performing dives, divers must both acquire the specific and complex movement patterns and demonstrate high levels of coordination. Thus, the ability to functionally adapt movement and coordinate during execution is proposed as enabling the skilled diver to produce consistently highly coordinated movement within what is regarded as a potentially highly variable and dynamic task (Bradshaw et al., 2007; Davids & Button, 2004). Divers have previously shown that they have the ability to regulate the duration and velocity of somersaults to within 1% of variability, producing a high degree of consistency in angular velocity during non-twisting multiple somersault dives (Sinclair et al., 2014).

The majority of research for the sport of springboard diving has been conducted on non-twisting somersault dives. This may be due to the complexity of the methodology that is required when analysing twisting somersault dives (Yeadon, 1990a), with the most common techniques requiring time consuming digitisation from multiple camera angles. The current case study aimed to examine the angular velocity profiles, key positional angles, and key event timings for a single athlete during the backward 2.5 somersaults with 1.5 twists (5352B). Furthermore the current study endeavoured to determine the 3D application of using inertial measurement units (IMU) during twisting dives.

METHOD: One internationally ranked male diver (height = 1.70m, mass = 67kg), was recruited for the study. Informed consent approved by the University of Sydney human ethics committee was obtained. Following a normal dry land warm-up, and as part of normal training, the diver completed 11 trials of the 5253B dives across four training sessions. In addition to the 5253B, 8 trials of a backward 2½ piked dive (205B) were collected in order to compare the twisting and non-twisting kinematics of the backward takeoff dives.

An inertial measurement unit, IMU, (IMeasureU, Ltd; Auckland, New Zealand) (dimensions 22 mm x 34 mm x 10 mm, mass = 12g) strapped to the divers' lower back (L4/L5) with a transparent film dressing (Opsite Flexigrid), was used to measure angular velocity profiles during the four training sessions. The IMU sample frequency was 100Hz. A comparison between IMU and 3D motion analysis (Cortex, 3.3) revealed <1% difference between the two motion capture systems, therefore the raw IMU output was used with no filtering. A custom Matlab script (The MathWorks, Inc., Natick, MA, USA) was used to export the individual dive data into Microsoft Excel (Microsoft Corp, Redmond, Washington, USA) to calculate peak angular velocities about the somersault and twist axes. Average angular velocity plateau and duration were also calculated for the twist portion of the dive. The angular velocity plateau was determined by an iterative procedure that identified the portion of the graph where the angular velocity was >90% of the plateau mean.

A high-speed Casio Exilim EX-FH100 camera was placed level with and perpendicular to the 3m springboard; with a frame rate of 120fps and a shutter speed of 1/250s. The field of view was limited to the diver's takeoff from the springboard, dive, and entry into the water. Video was digitised using Tracker software (Brown, 2008). A calibration frame, 7m x 3m, (Sinclair, Walker & Rickards, 2012) was used to transform digitised coordinates into real world coordinates. Takeoff and entry angles were calculated from digitised coordinates. Takeoff angle was defined as the line between the ankle and iliac crest with respect to the right hand horizontal. Entry angle was defined as the line between the iliac crest and the shoulder with respect to the right hand horizontal. Relative hip angles were calculated at takeoff, somersault, and entry and were defined as the angle between the thigh and trunk segments. Total flight time was calculated and measured from the final frame of foot contact with the springboard to the first frame where hands broke the water on entry (Sanders & Gibson 2000). Time durations between key events were also calculated from takeoff to somersault initiation, from the somersault to the initiation of somersault opening and from the somersault opening to water entry.

Coefficient of variation calculated the level of intra-variability and an independent T-test determined whether there were any significance differences ($p \leq 0.05$) between the 205B and 5253B.

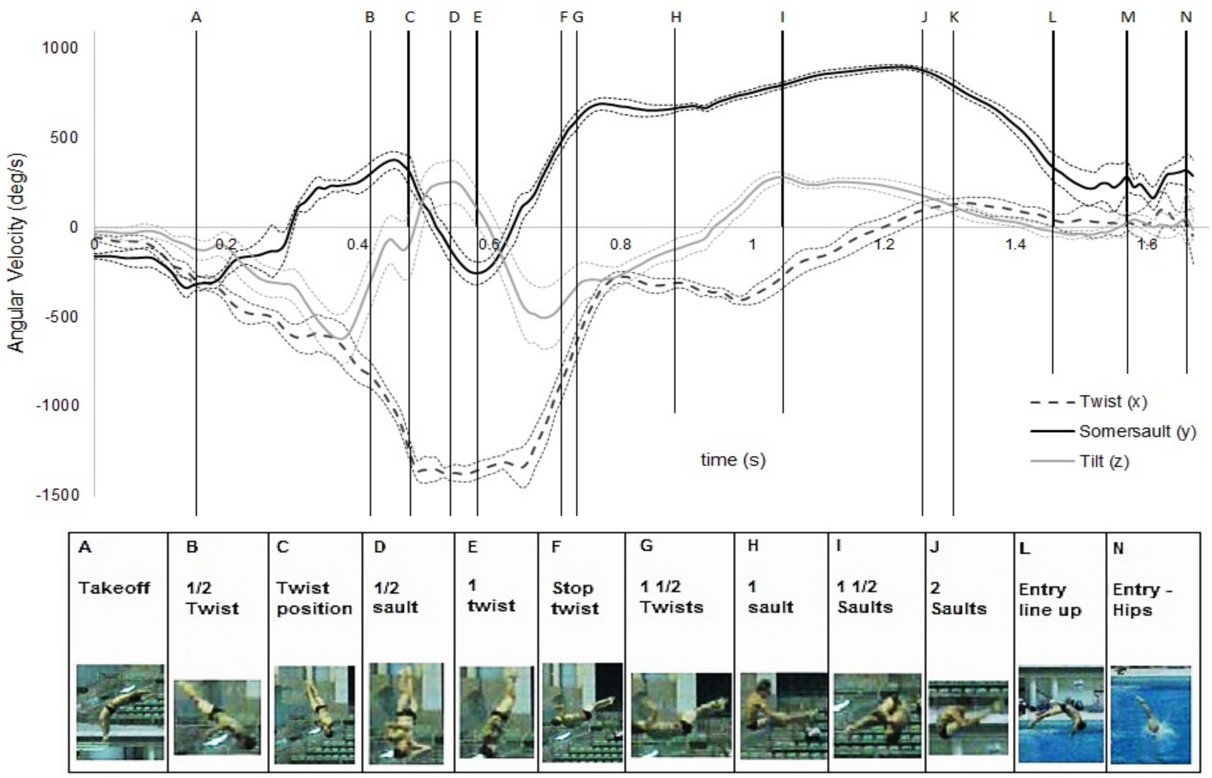
RESULTS AND DISCUSSION: The gyroscopes in the IMU provided tri-axial angular velocity data for a twisting somersault dive (Figure 1.) They provided a clear distinction between the somersault rotations about the transverse axis, the twisting rotations about the longitudinal axis and the body's tilt.

To produce a twist about the longitudinal axis two techniques can be used; contact and aerial. Divers performing backward twists have been shown to use a combination of both techniques (Yeadon, 2001). The diver in this case study set the twisting motion prior to flight by turning their arms and torso in the direction of the twist (A, Figure 1). Once in the air the diver performed asymmetrical arm movements that were followed by arm adduction at the ¼ twist position to increase the tilt angle and therefore the rate of twist (B-C, Figure 1). During the twisting motion the somersault rotation fluctuated between negative and positive angular velocity (A-F Figure 1). This is due to the orientation of the body with respect to the fixed transverse axis. At each ½ twist increment the orientation changes, resulting in the fluctuation. The peak twisting angular velocity was -1435±28 deg/s, with 2% movement variability. The angular velocity plateau was highly consistent, 0.9%, with an average of -1347±12 deg/s, and a duration of 0.18±0.02s.

Once the 1½ twist rotations are complete the diver performs hip flexion to slow the rate of twist by increasing the moment of inertia about the longitudinal plane. Therefore, reducing the moment of inertia about the transverse axis and increasing the somersault angular velocity (F-

H, Figure 1). Hip flexion in conjunction with anteroposterior rotation of the arms also helps to realign the rotation about the transverse axis in preparation for a straight entry (Sanders & Wilson, 1987). The odd number of twists results in the diver's somersault being performed in the forward direction. In accordance with the conservation of angular momentum, the direction of somersault rotation remained unchanged with respect to the external frame (Sanders 1999). The somersault angular velocity profile showed two obvious peaks. The first peak coincides with the initiation of the hip flexion (near G, Figure 1) and the second peak coincides with the second somersault rotation (J, Figure 1). The average angular velocity was 697±33 deg/s at peak one and 900±11 deg/s at peak two, with a variability measure of 4.8% and 1.3% respectively. When comparing the rational speeds of the twisting and non-twisting dive, the 5253B had 62 deg/s greater angular velocity at peak two, p=0.000. Angular momentum has been found to be greater for twisting dives when compared to non-twisting dives (Sanders and Wilson 1987). Thus, once the twist has stopped, the angular momentum is transferred purely to the somersault axis, which may result in the increased angular velocity when compared to the non-twisting dive.

Figure 1: IMU Angular velocity profile of the 5253B dive. Solid line represents the mean from 11 trails and the dotted line represents the standard deviation. A – takeoff, B – ½ twist, C – twist position (arms in), D - ½ somersault rotation, E - 1 twist, F - stopping twist and starting to form pike position, G - 1½ twists, H - 1 somersault, I - 1 ½ somersaults, J - 2 somersaults, K - Open from somersault, L - extension; entry line up, M - Hands entry, N - Hip entry.



The 2D video analysis of the somersault axis revealed 13° greater extension about the hip at takeoff when performing the 5253B dive (Table 1). The somersault position showed no significant difference (p=0.34), illustrating the diver performs a comparable tight pike position during both dives. The diver was in a straighter body alignment at hand contact with the water when performing the 5253B. This may be due to the dive finishing in the forward direction allowing them to "spot" the water in preparation for entry. There was a reduction in total time of flight, dive height and dive distance for the 5253B dive. This may be due to the increased angular momentum required to perform the additional 1½ twists during the backward 2½ somersaults (Sanders and Wilson 1987). The increased hip angle at takeoff for the 5253B corresponds to this theory. The ratio of linear to angular momentum may be reduced in order to develop the increased rotational demands resulting in greater elastic strain energy from the springboard being transferred to the rotational aspect of the dive rather than translation. The key event timings during the dive flight were different due to the requirements of the movement patterns for each dive type.

The total time of flight variability measured at <1% for both dives, however the variability ranged between 2-12% for the timings of the key events. It appears that the diver was able to adapt to variations during these key events to allow for a consistent dive duration in order to successfully complete the required movement patterns.

Table 1: Mean, standard deviation and coefficient of variation (parentheses) for 2D kinematic measures taken from video footage.

Dive	**205B**	**5253B - Somersault axis (y)**
N	8	11
Takeoff angle (deg) *	74.4 ± 1.5 (2.1%)	76.1 ± 1.6 (2.1%)
Takeoff – hip angle (deg) **	138.6 ± 2.6 (1.9%)	125.3 ± 3.2 (2.6%)
Somersault hip angle (deg)	38.6 ± 2.2 (5.7%)	39.31 ± 2.51 (6.4%)
Entry angle (deg) **	102.5 ± 3.8 (3.7%)	121.5 ± 4.3 (3.5%)
Entry - hip angle (deg) **	132.9 ± 4.1 (3.1%)	158.1 ± 8.2 (5.2%)
Time of flight (s) **	1.40 ± 0.01 (0.7%)	1.37 ± 0.01 (0.6%)
Takeoff to sault position (s) **	0.31 ± 0.01 (3.2%)	0.71 ± 0.01 (2.0%)
Sault position to open (s) **	0.56 ± 0.04 (7.1%)	0.37 ± 0.05 (12.3%)
Open to entry (s) **	0.53 ± 0.04 (7.5%)	0.29 ± 0.03 (10.5%)
Dive height (m) **	1.30 ± 0.10 (7.7%)	0.96 ± 0.06 (6.1%)
Dive distance (m) **	2.29 ± 0.22 (9.5%)	2.06 ± 0.12 (6.0%)

Statistical difference between the means; *p<0.05, **p<0.01

CONCLUSION: Inertial measurement units provide a quick and practical analysis tool for coaches wanting to monitor their athlete's daily performance for both twisting and non-twisting dives. The 5253B dive is a highly complex dive that requires increased mechanical and physical abilities to develop the necessary momentum to successfully perform this dive. Our athlete was able to successfully complete this complex dive to an international standard at a high level of consistency with less than 2% variability at peak angular velocity about both the twist and somersault axis, and less than1% variability shown in dive flight time.

1st Symposium for Researchers in Diving. 2013
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THE EFFECT OF SPRINGBOARD FULCRUM SETTING ON A DIVER'S KINEMATICS

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Introduction

Springboard diving is an early specialisation sport with peak performance ranging between 14-18 years old for females and 18-22 years old for males (Bompa & Haff, 2009). An athlete must specialise in diving at young age to develop the required motor patterns to be able to perform complex manoeuvres.

The forward dive category is classified as a forward running approach. The approach can be broken down into four phases; the run, hurdle stance, hurdle flight and takeoff stance. The approach requires a diver to take at least two to three fast steps followed by a push off one foot into the hurdle flight. During takeoff the diver applies a downward force to maximally depress the springboard. Following maximum depression the diver rides the springboard as it is recoiled, allowing them to be projected up and slightly forward into the dive flight.

An adjustable fulcrum supports the springboard. The fulcrum has a scale of 1-9, with 1 being the stiffest setting and 9 the loosest setting (Miller, Osborne, Jones, 1998). As the springboard is moved back to a looser fulcrum setting the compliance and the effective mass of the springboard is increased Sprigings, Watson, et al., 1989).

The potential energy of the springboard is known as strain energy. The springboard has a linear stress-strain relationship, which allows it to return to its original position after going through a downward deformation, (Sprigings et al. 1989). The springboard will convert the kinetic energy of the diver at touchdown into strain energy during the depression and this energy is then returned to the diver during the recoil of the springboard (Sanders and Wilson 1988) to gain maximum dive height. The amount of energy that is placed into the spring system is proportion the amount of kinetic energy transferred to the springboard from a diver's vertical velocity at touchdown and the magnitude of force the diver adds to the system by actively pushing the springboard down towards the water (Miller, 1981; Sanders and Wilson 1987). A diver's joint angles at touchdown will indicated the amount of extension range of motion that is available to the diver to actively push the springboard down towards the water (Sanders, and Wilson 1988).

Current literature focuses on senior international athletes with only one paper providing a comparison between junior and senior athletes (Miller et al, 1998). This paper reported that junior elite divers choose a fulcrum setting at a stiffer value. The current investigation aims to determine whether changing the fulcrum setting for junior elite divers will impact their overall outcome dive height.

Method

Eight divers from the New South Wales Institute of Sport (NSWIS) were recruited**.** The diver's were required to perform three forward 1 ½ piked somersault dives (103B) at three different fulcrum settings, their preferred, minus one (tight) and plus one (loose) from this setting. Non-toxic water proof paint was used to mark each subject's anatomical landmarks; head of the 5th metatarsal, lateral malleolus of the fibular, lateral condyle of the femur, middle iliac crest, greater tubercle of the humerus, lateral epicondyle of the humerus and head of the ulnar on the side of the hurdle support leg. To calculate each subject's centre of mass, 95 anthropometric measurements were taken from the upper limb, lower limb, trunk and head. The method followed Yeadon's mathematical inertia model of the human body (Yeadon, 1990b).

High-speed (210 fps) two-dimensional video footage was digitised and analysis (Video4Coach 2009), to determine the lower limb joint angles, centre of mass displacement, centre of mass vertical velocity, work and dive height. The ankle, knee and hips angles were measured at touchdown, maximum depression and takeoff. The work performed by the diver to gain height was defined as the some of the change in kinetic energy and potential energy at the instants of touchdown and takeoff Sanders & Wilson, 1988). Dive height (DH) was defined as the difference between the height of the centre of gravity at takeoff and peak dive height.

Statistical differences in the kinematic variables were assessed using two way Analysis of Variance with repeated measures (PASW Statistics, Version 18). The main effects of fulcrum setting (preferred, tight and loose) and trial number (1, 2, and 3) were assessed using $P \leq 0.05$ as the requirement for statistical difference.

Results

As the diver descends from the hurdle flight they begin to dorsiflex their ankles in conjunction with flexing their knees and hips to prepare for touchdown. The joints continue to flex to absorb the landing impact force for a short period of time. The diver then extends their joints to maximally press the springboard down towards the water. At the takeoff the ankles are plantar flexed, the knees are at full or near full extension. The hips are in a partially flexed position at takeoff to generate the angular momentum for the required dive proceeding takeoff, Figure 1.

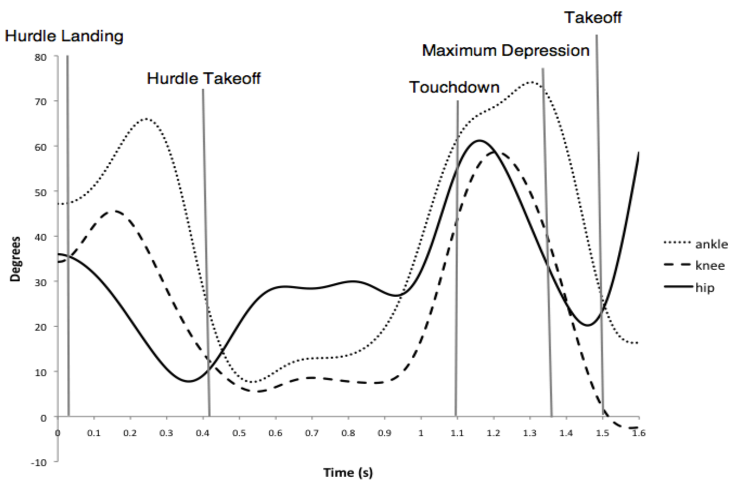

Figure 1, Lower limb joint angles during the forward running approach

The looser fulcrum resulted in greater plantar flexion in the ankle at maximum depression ($p = 0.04$). The looser fulcrum also resulted in greater flexion in the knee at touchdown ($p = 0.037$) and great extension at maximum depression ($p = 0.00$). This resulted in the divers having greater range of motion about the knee for a looser fulcrum setting (figure 1). There were no significant changes in the hip at touchdown or maximum depression. During the takeoff no significant differences were found in the lower limb joint angles.

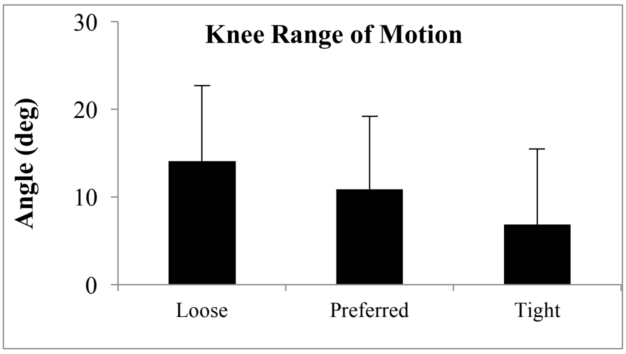

Figure 2, Knee range of motion between the touchdown and maximum depression

The looser fulcrum setting resulted in a larger downward deflection of the tip of the springboard ($p = 0.035$). Vertical downward deflection increased by approximately 0.03m when the fulcrum was moved back from the tight to loose fulcrum setting.

The mean potential energy at each fulcrum setting ranged between 17.16-17.61 $J.kg^{-1}$ at touchdown and 18.60-18.69 $J.kg^{-1}$ at takeoff. Kinetic energy ranged between 5.94-6.34 $J.kg^{-1}$ and 8.34-8.45 $J.kg^{-1}$ at touchdown and takeoff respectively. The relative of change in kinetic energy between touchdown and takeoff was larger than potential energy, thus kinetic energy played a larger role in the amount of work done to gain peak dive height. There was, however, no significant difference between fulcrum settings for work performed to gain peak height ($p=0.22$) and subsequently no change in dive height ($p=0.191$).

Discussion

The significant joint angle data revealed that divers had greater knee range of motion for a looser fulcrum setting at the key energy generation phases of touchdown and maximum depression. There was also a greater depression of the springboard for the looser fulcrum setting. In theory, it was expected that a larger amount of work would be performed on the springboard with a looser fulcrum setting, resulting in the vertical velocity at takeoff being higher (Jones and Miller 1996) and subsequently a greater dive height.

The change in the springboard oscillation cycle time could be a reason as to why no significant benefits were seen. As the springboard becomes looser the oscillation cycle time will increase (Miller 1998). A diver must be able to increase their hurdle flight time in order to catch the springboard at its optimal position of maximum downward vertical velocity (Jones and Miller 1996; Miller, Osborne et al. 1998). Catching the springboard at this position will minimise the difference between the velocities of the diver's feet and the tip of the springboard at the impact of touchdown. This will allow the springboard to be driven down to the water faster. If a diver catches the springboard during its upward motion, also known as ‘stamping the board’, there would be more energy lost during higher impact velocities. The quadriceps would therefore be performing a great negative workload, resulting in a great absorption of the potential energy.

The strength of the divers could have also impacted their ability to place additional energy into the spring system. As a diver touches down with the springboard they will experience a flexion torque about the knee caused by the springboard reaction forces (Sanders and Gibson 2000). A diver must overcome this flexion torque by providing a greater knee extension torque to push the springboard down towards the water. From the current results we know that when the fulcrum becomes looser the knee flexion increases therefore it can be assumed that the flexion torque will also increase. If junior divers do not have the adequate strength to counteract the increase in the flexion torque they will experience an eccentric absorption of their potential energy and will be unable to apply additional energy into the spring system.

The mass of junior divers could be a third reason as to why no increase was found. Junior divers are generally a smaller stature than that of their senior counterparts. The weight force of these athletes is therefore smaller. At a set fulcrum setting it is known that as the load increases the downward deflection of the springboard is increased (Sprigings, Stilling et al 1989). Disregarding the strength of the junior divers, the reduced weight force of these athletes could be impacting the amount of deflection these divers are achieving during maximum depression and therefore potential strain energy during the maximum depression.

The final reasoning behind why we saw no significant results in the work performed on the springboard and subsequently the diver height could be due to intra and inter variation of resulting data. Figure 2 represents the inter-variability of the resulting data. Some subjects were unable to maintain the same amount of work performed on the springboard at the looser fulcrum setting, subsequently there was no increase in the dive height. As springboard depression is increase the energy storage and return should be increased, however the divers that performed less work at the looser fulcrum setting ruled out any benefit from the increased storage. They may not have been able to successfully apply a strong extension torque to over the increase in flexion torque about the knee at touchdown.

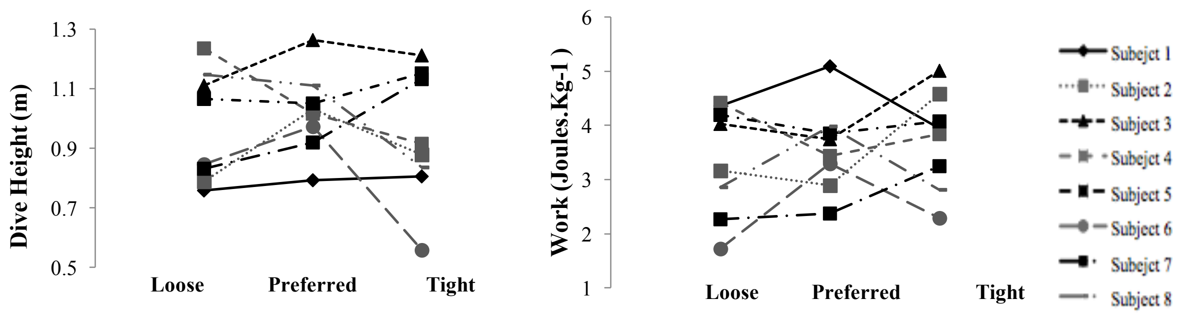

Figure 3, Inter-variability of the work performed on the springboard and the dive height. Each line represents the average work and dive height for a single subject performed on the springboard for each fulcrum setting

Conclusion

Junior elite divers were unable to successfully use the increased knee extension range of motion and downward deflection of the springboard to apply additional energy into the spring system. Subsequently there was no change in dive height. The current findings suggest that junior divers may not have the correct technique, timing or strength to overcome the change in the springboard mechanics as well as the increase in flexion torque about the knee.

References for these conference papers are included in the list of references at the end of this thesis

Appendix 7
Research into action fund

2014
Successful grant application

Title

The development of a somersaulting frame to train divers to the high rotational velocities required for international performance.

Summary of project for public release:

Divers are now required to somersault at 1100+ degrees per second for the higher degree of difficulty dives and it is a challenge to learn this skill safely. This project is focussed on the development of a somersaulting frame allowing athletes to safely develop their somersaulting and aerial awareness skills.

Contribution to project

Cherie Walker, PhD Student (University of Sydney), Diving Biomechanics, "Bodies in Space" ARC Linkage project and Part-time NSWIS staff member. Former gymnastics and current diving coach whose PhD research is being used by the NSWIS and Australian diving programs. Will work with the coaches on the use of the equipment and to implement her research findings into athlete development.

Role

- Delivering biomechanical research to engineering team
- Continuous communication with project team
- Set up of the device
- Teach coaches and athletes safety protocol
- Observation of training

Appendix 8
Human Research Ethics

Ethics reference number: 2013/762

THE UNIVERSITY OF SYDNEY

Research Integrity
Human Research Ethics Committee

Monday, 14 October 2013

Dr Peter Sinclair
Exercise Health and Performance; Faculty of Health Sciences
Email: peter.sinclair@sydney.edu.au

Dear Dr Peter Sinclair

I am pleased to inform you that the University of Sydney Human Research Ethics Committee (HREC) has approved your project entitled "**The variability of key kinematic variables of a diver's approach, takeoff and flight in springboard diving**".

Details of the approval are as follows:

Project No.: **2013/762**

Approval Date: **11 October 2013**

First Annual Report Due: **12 October 2014**

Authorised Personnel: **Sinclair Peter; Cobley Stephen; Graham Kenneth; Walker Cherie;**

Documents Approved:

Date Uploaded	Type	Document Name
05/07/2013	Questionnaires/Surveys	Synrchonised diving questionnaire
04/07/2013	Advertisements/Flyer	ARC linkage programs – Bodies in Space
26/07/2013	Advertisements/Flyer	Part 2: Synchronised diving – Aus Champs; consent parent
26/07/2013	Participant Consent Form	Part 1: Dive flight Variability: Consent form
26/07/2013	Participant Consent Form	Part 1: Dive flight Variability: Parental consent form
08/10/2013	Participant Consent Form	Amended consent form for part 2a of the study
08/10/2013	Participant Consent Form	Amended consent form for part 2a of the study (parent)
08/10/2013	Participant Info Statement	Amended PIS for part one of the study
08/10/2013	Participant Info Statement	Amended PIS for part one of the study (parent)
08/10/2013	Participant Info Statement	Amended PIS for part 2a of the study

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CRICOS 00026A

THE UNIVERSITY OF SYDNEY

08/10/2013	Participant Info Statement	Amended PIS for part 2a of the study (parent)
08/10/2013	Participant Info Statement	Amended PIS for part 2b of the study
08/10/2013	Participant Info Statement	Amended PIS for part 2b of the study (parent)

HREC approval is valid for four (4) years from the approval date stated in this letter and is granted pending the following conditions being met:

Condition/s of Approval

- Continuing compliance with the National Statement on Ethical Conduct in Research Involving Humans.
- Provision of an annual report on this research to the Human Research Ethics Committee from the approval date and at the completion of the study. Failure to submit reports will result in withdrawal of ethics approval for the project.
- All serious and unexpected adverse events should be reported to the HREC within 72 hours.
- All unforeseen events that might affect continued ethical acceptability of the project should be reported to the HREC as soon as possible.
- Any changes to the project including changes to research personnel must be approved by the HREC before the research project can proceed.

Chief Investigator / Supervisor's responsibilities:

1. You must retain copies of all signed Consent Forms (if applicable) and provide these to the HREC on request.
2. It is your responsibility to provide a copy of this letter to any internal/external granting agencies if requested.

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Professor Glen Davis
Chair
Human Research Ethics Committee

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007), NHMRC and Universities Australia Australian Code for the Responsible Conduct of Research (2007) and the CPMP/ICH Note for Guidance on Good Clinical Practice.

THE UNIVERSITY OF SYDNEY

Research Integrity
Human Research Ethics Committee

Thursday, 11 September 2014

Dr Peter Sinclair
Exercise Health and Performance; Faculty of Health Sciences
Email: peter.sinclair@sydney.edu.au

Dear Peter

Your request to modify the above project submitted on 25 June 2014 was considered by the Executive of the Human Research Ethics Committee at its meeting on **3 September 2014**.

The Committee had no ethical objections to the modification/s and has approved the project to proceed.

Details of the approval are as follows:

Project No.: **2013/762**

Project Title: **The variability of key kinematic variables of a diver's approach, takeoff and flight in springboard diving**

Approved Documents:

Date Uploaded	Type	Document Name
30/07/2014	Participant Info Statement	PIS - Parent version 4
30/07/2014	Participant Info Statement	PIS version 4

Special Condition of Approval:

Please correct the following minor errors in the PIS prior to distribution:

- What does the study involve? "…The testing procedure requires a record of your child's age"
- How much time will the study take? "….The testing procedure will be conducted during 3-5 of your child's … "

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Helen Mitchell

Chair
Human Research Executive Committee

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007), NHMRC and Universities Australia Australian Code for the Responsible Conduct of Research (2007) and the CPMP/ICH Note for Guidance on Good Clinical Practice.

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The variability of key kinematic variables of a diver's takeoff and flight in springboard diving

PARTICIPANT INFORMATION STATEMENT

(1) What is the study about?

You are invited to participate in a study examining the variability of a springboard diver's movement pattern during the takeoff and flight of multiple somersault dives. The study will investigate the biomechanical effects of variability during the takeoff and dive flight. It will aim to determine how variability will affect an athlete's overall performance.

(2) Who is carrying out the study?

The study is being conducted by Dr. Peter Sinclair and Cherie Walker in association with the University of Sydney and the NSW Institute of Sport (NSWIS).

(3) What does the study involve?

If you agree to participate in this study, Dr. Peter Sinclair and associates will require you to attend the Sydney Olympic Park Aquatic Centre (SOPAC). Your regular routine from the 3m springboard will be record during 3-5 of your training sessions. You will be provided time to perform your regular warm up program prior to the commencement of the testing session. A familiarization period with the chosen 3m springboard will also be provided.

There is always a potential risk of injury while diving. However the risk involved in this study is no greater than that of your regular training schedule and the likelihood of injury is limited as the required dives are a part of your regular training session. If you do not feel confident or comfortable in performing a dive, you are not required to do so.

The testing procedure requires a record of your age, height and weight to be taken in order to determine the general subject characteristics. Athletic strapping tape will be used to mark and locate your foot, knee and hip. The tip of the springboard will also be marked. High speed cameras will be used to record your takeoff, dive flight and entry during your regular 3m training sessions. In addition, small waterproof electronic devices, 35mm x 20mm x 9mm, will be secured to your lower back via strapping tape to measure the speed of rotation of your body. Computer analysis of the video and inertial data will enable the position of your body to be determined throughout the takeoff and dive. This will allow the calculation of timings, hip angles, velocities and accelerations at key phases during your takeoff and dive flight. A qualified judge will be present to score your dive performance.

(4) How much time will the study take?

The testing procedure will be conducted during 3-5 of your regular training sessions. During each session you will be provided your regular allocated time to complete your warm up program. Once your warm up is complete 15 minutes will be allocated to the application of the strapping tape markers and inertial sensors. You will then be provided a 5 minute familiarisation with the chosen springboard. The remaining time will be allocated to your regular training routine.

(5) Can I withdraw from the study?

Being in this study is completely voluntary - you are not under any obligation to consent and - if you do consent - you can withdraw at any time without affecting your relationship with The University of Sydney and/or the New South Wales Institute of Sport (NSWIS).

(6) Will anyone else know the results?

All aspects of the study, including results, will be strictly confidential and only the researchers, sports science committee at NSWIS and your diving coach will have access to information. A report of the study may be submitted for publication, but individual participants will not be identifiable in such a report.

(7) Will the study benefit me?

The findings may point out general information on the key features during the takeoff and dive flight that could lead to improvements in the performance of multiple somersault dives from the 3m springboard. This could potentially lead to the ability to increases your dive degree of difficulty. We, however, cannot and do not guarantee or promise that you will receive any benefits from the study.

(8) Can I tell other people about the study?

You are not under any obligation to keep this study confidential.

(9) What if I require further information about the study or my involvement in it?

When you have read this information, Cherie Walker will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact Dr. Peter Sinclair at 9351 9724 or Cherie Walker at 97630629.

(10) What if I have a complaint or any concerns?

Any person with concerns or complaints about the conduct of a research study can contact The Manager, Human Ethics Administration, University of Sydney on +61 2 8627 8176 (Telephone); +61 2 8627 8177 (Facsimile) or ro.humanethics@sydney.edu.au (Email).

This information sheet is for you to keep

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The variability of key kinematic variables of a diver's takeoff and flight in springboard diving

PARENTAL (OR GUARDIAN) INFORMATION STATEMENT

(1) What is the study about?

You are invited to permit your child to participate in a study examining the variability of a springboard diver's movement pattern during the takeoff and flight of multiple somersault dives. The study will investigate the biomechanical effects of variability during the takeoff and dive flight. It will aim to determine how variability will affect an athlete's overall performance. Your child was selected as they have competed at state or national elite championships.

(2) Who is carrying out the study?

The study is being conducted by Dr. Peter Sinclair and Cherie Walker in association with the University of Sydney and the NSW Institute of Sport (NSWIS).

(3) What does the study involve?

If you agree to participate in this study, Dr. Peter Sinclair and associates will require your child to attend the Sydney Olympic Park Aquatic Centre (SOPAC). Your child's regular routine from the 3m springboard will be record during 3-5 of their training sessions. Your child will be provided time to perform their regular warm up program prior to the commencement of the testing session. A familiarization period with the chosen 3m springboard will also be provided.

There is always a potential risk of injury while diving. However the risk involved in this study is no greater than that of your child's regular training schedule and the likelihood of injury is limited as the required dives are a part of their regular training session. If your child does not feel confident or comfortable in performing a dive they are not required to do so.

The testing procedure requires a record your child's age, height and weight to be recorded in order to determine the general subject characteristics. Athletic strapping tape will be used to mark and locate their foot, knee and hip. The tip of the springboard will also be marked. High speed cameras will be used to record your child's takeoff, dive flight and entry during their regular 3m training sessions. In addition, small waterproof electronic devices, 35mm x 20mm x 9mm, will be secured to your child's forearm, arm, upper back and lower back, thigh and shank via strapping tape to measure the speed of rotation of their body. Computer analysis of the video and inertial data will enable the position of their body to be determined throughout the takeoff and dive. This will allow the calculation of timings, hip angles, velocities and accelerations at key phases during their takeoff and dive flight. A qualified judge will be present to score your child's dive performance.

(4) How much time will the study take?

The testing procedure will be conducted during 3-5 your child's regular training sessions. Your child will be provided their regular allocated time to complete their warm up program. Once their warm up is complete 15-20 minutes will be allocated to the application of the strapping tape markers and inertial sensors. Your child will then be provided a 5 minute familiarisation with the chosen springboard. The remaining time will be allocated to your child's regular training routine.

(11) Can my child withdraw from the study?

Being in this study is completely voluntary. You are not under any obligation to consent your child. Your decision whether or not to permit your child to participate will not prejudice you or your child's future relations with The University of Sydney. If you decide to permit your child to participate, you are free to withdraw your consent, and to discontinue your child's participation at any time without affecting your relationship with the University of Sydney and/or the New South Wales Institute of Sport (NSWIS).

(12) Will anyone else know the results?

All aspects of the study, including results, will be strictly confidential and only the researchers, sports science committee at NSWIS and your child's diving coach will have access to information. A report of the study may be submitted for publication, but individual participants will not be identifiable in such a report.

(13) Will the study benefit my child?

The findings may point out general information on the key features during the takeoff and dive flight that could lead to improvements in the performance of multiple somersault dives from the 3m springboard. This could potentially lead to the ability for your child to increase their dive degree of difficulty. We, however, cannot and do not guarantee or promise that they will receive any benefits from the study.

(14) Can I tell other people about the study?

You are not under any obligation to keep this study confidential.

(15) What if I require further information about the study or my involvement in it?

When you have read this information, Cherie Walker will discuss it with you further and answer any questions you may have. If you would like to know more at any stage, please feel free to contact Dr. Peter Sinclair at 9351 9724 or Cherie Walker at 97630629.

(16) What if I have a complaint or any concerns?

Any person with concerns or complaints about the conduct of a research study can contact The Manager, Human Ethics Administration, University of Sydney on +61 2 8627 8176 (Telephone); +61 2 8627 8177 (Facsimile) or ro.humanethics@sydney.edu.au (Email).

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PARTICIPANT CONSENT FORM

I, ...[PRINT NAME], give consent to my participation in the research project

The variability of key kinematic variables of a diver's takeoff and flight in springboard diving

In giving my consent I acknowledge that:

1. The procedures required for the project and the time involved have been explained to me, including any inconvenience, risk, discomfort or side effect, and their implications, and any questions I have about the project have been answered to my satisfaction.

2. I have read the Participant Information Statement and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

3. I understand that being in this study is completely voluntary – I am not under any obligation to consent.

4. I understand that my involvement is strictly confidential. I understand that any research data gathered from the results of the study may be published however no information about me will be used in any way that is identifiable.

5. I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher(s), the University of Sydney, Diving Australia and/or the New South Wales Institute of Sport now or in the future.

6. I consent to:

- Video-recording: YES ☐ NO ☐
- Questionnaire recording: YES ☐ NO ☐
- Receiving Feedback : YES ☐ NO ☐

If you answered YES to the "Receiving Feedback" question, please provide your details i.e. mailing address, email address.

Feedback Option

Address: ______________________________

____

Email: ______________________________

....
Signature

....
Please PRINT name

....
Date

Dr. Peter Sinclair

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PARENTAL (OR GUARDIAN) CONSENT FORM

I,...[PRINT NAME], agree to permit ....……..[PRINT CHILD'S NAME], who is aged .... years, to participate in the research project

The variability of key kinematic variables of a diver's takeoff and flight in springboard diving

In giving my consent I acknowledge that:

1. The procedures required for the project and the time involved for my child's participation in the project have been explained to me, and any questions I have about the project have been answered to my satisfaction.

2. I have read the Information Statement and have been given the opportunity to discuss the information and my child's involvement in the project with the researcher/s.

3. I understand that being in this study is completely voluntary – I am not under any obligation to consent to my child's participation.

4. I understand that my child's involvement is strictly confidential. I understand that research data gathered from the results of the study may be published however no information about my child nor I will be used in any way that is identifiable.

5. I understand that I can withdraw my child from the study at any time without prejudice to me or my child's relationship with the researcher/s, the University of Sydney, Diving Australia and/or the New South Wales Institute of Sport now or in the future.

6. I consent to:

- Video recording: YES ☐ NO ☐
- Questionnaire recording: YES ☐ NO ☐

- Receiving Feedback: YES ☐ NO ☐

If you answered YES to the "Receiving Feedback" question, please provide your details i.e. mailing address, email address.

Feedback Option

Address: ____________________

____

Email: ____________________

....
Signature of Parent/Caregiver

....
Please PRINT name

....
Date

....
Signature of Child

....
Please PRINT name

....
Date

The variability of key kinematic variables of a diver's takeoff and flight in springboard diving, Parent Version [2, 09/09/2013]

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