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DOCTORAL THESIS

A biomechanical analysis of the BMX SX gate start.

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A biomechanical analysis of the BMX SX gate start

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Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy (PhD)

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Abstract

Bicycle Motor Cross (BMX) Supercross (SX) racing is a relatively new sport with little formal research to support it. A fast start is critical to race performance as an advantage in the first few seconds allows the athlete to select the optimal line into the first jump. Research suggests that the first athlete to land the first jump is the most likely to win the race. Given this known association, a considerable amount of training time is devoted to practising the start action and training the related muscle groups. A key performance outcome for the gate start is the kink time, that is the time split from the start gate to the change in gradient on the SX start ramp at ~ 3 m. Little is known about the mechanics of the optimal start action. This thesis presents five studies that provide insight into the determinant phases and kinematics of the BMX SX start action and investigates whether race start reaction time (RT) can be improved with training. A key aim of this thesis was to provide pragmatic research for coaches and athletes on means to optimise the BMX SX gate start action. As such, feasibility and ecological validity of all studies were directed to maintain a coach/athlete centric focus. This program of research was conducted in collaboration with the Cycling Australia BMX unit.

In the first study, the BMX SX start action was divided into distinct phases. The temporal invariability of the phases within, and between, five BMX SX World Class (WC) athletes was examined. WC athletes were considered to be those who had achieved a podium finish in Union Cycliste Internationale (UCI) competition during the year of testing, whereas Elite athletes had a UCI ranking but no podium finish at UCI international level. The study demonstrated that the phase most likely to relate to performance for this cohort was the weight transfer of the second crank. Using the phases defined in Study 1, Study 2 was undertaken to examine the differences in absolute and relative phase duration between WC and Elite athletes, and male and female athletes. The results of the second study identified that the WC athletes had faster second crank weight transfer times than the Elite athletes, and that the male athletes had a faster first crank, second crank weight transfer and power stroke time, and greater temporal variation than the female athletes.

Findings from both studies identified that the reaction time (RT) phase may account for ~ 7% of the total gate start action.

The third study was an intervention study with the aim of reducing the race start RT. The intervention consisted of a two-week training intervention program (14 sessions) following which the difference in RTs between the intervention group (n = 4) and a control group (n = 5) were compared with the pre-intervention measures. Whilst the RT on the training device was shown to improve for the intervention group (but not the control group), this did not transfer to a clear improvement in race start RT on the ramp or the kink time (i.e. performance outcome).

The final two studies focused on the athlete kinematics of the gate start action. The results of Study 4 showed that the markerless motion capture method was valid to within 2˚ and had an intra-tester reliability within 6˚ across five joint angles (ankle, knee, hip, elbow, shoulder) and two segment angles (head and torso). The aim of the final study (Study 5) was to use kinematics to describe a ‘fast’ gate start for 14 WC and Elite athletes. The validated markerless motion capture method as described in Study 4 was used to maintain ecological validity (n = 14, 5 trials each). Three key set (i.e. starting) positions were identified; the *upright, back* and *angled*. Three key hub trajectory shapes were also identified: *hairpin*, *up and over*, and *half circle*. The set position was linked to performance with the *back* set position being favoured by the faster athletes. The *back* set position was most likely to result in the *hairpin* hub trajectory, which was also used by the fastest athletes. Thus a ‘fast’ gate start action was characterised by the *back* set position and moved through a *hairpin* hub trajectory for this cohort.

The conclusion of the thesis is that the set position is critical to the execution of the BMX SX gate start action. The *back* set position is most likely to result in a fast gate start as it enables the body to most efficiently execute the second crank weight transfer phase which was shown to relate to gate start performance.

Keywords: kinematics, sports biomechanics, performance analysis, motion capture, cycling, skill acquisition

Declaration by author

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Doctor of Philosophy by Research.

I declare that the research presented within this thesis is a product of my own original ideas and work and contains no material which has previously been submitted for a degree at this university or any other institution, except where due acknowledgement has been made.

Josephine Anne Grigg

14 February 2019

Declaration of author contributions

Journal Article: The validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX Supercross gate start

Authors	Concept & Design	Data Collection	Data Analysis	Drafting of Manuscript	Critical Revision
Grigg	70	90	100	70	60
Haakonssen	10	10		10	10
Rathbone	10				
Orr				10	10
Keogh	10			10	20

Journal Article: Literature review: Kinematics of the BMX SX gate start

Authors	Concept & Design	Data Collection	Data Analysis	Drafting of Manuscript	Critical Revision
Grigg	60	100	100	70	60
Haakonssen	10			10	10
Orr	20			10	10
Keogh	10			10	20

Book Chapter: Determinant phases of the BMX SX gate start action

Authors	Concept & Design	Data Collection	Data Analysis	Drafting of Manuscript	Critical Revision
Grigg	90	90	100	70	70
Haakonssen	10	5		10	10
Orr				10	10
Bootes	10	5			
Keogh				10	10

Publication and conference presentations

Journal Articles

The validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX Supercross gate start

Grigg, J., Haakonssen, E., Rathbone, E., Orr, R. & Keogh, J. W. L. 2018 In: Sports Biomechanics. 17, 3, p. 383-401

Literature review: Kinematics of the BMX SX gate start

Grigg, J., Haakonssen, E., Orr, R. M. & Keogh, J. W. L. 2017 In: Journal of Science and Cycling. 6, 1, p. 3-10.

Book chapter accepted for publication

Determinant phases of the BMX SX gate start action

Grigg, J., Haakonssen, E., Orr, R. M., Bootes, W. & Keogh, J. W. L. (In Press) Biomechanics of Cycling (2nd Edn) ed. Bini, R. & Hume, P., Springer, Australia

Conferences

Kinematics of the BMX SX gate start action

Grigg, J., Haakonssen, E., Orr, R. M., Bootes, W. & Keogh, J. W. L. 10 Sep 2018 *36th Conference of the International Society of Biomechanics in Sports Conference Proceedings.* Hume, P. A., Alderson, J. & Wilson, B. (eds.). Auckland University of Technology, 4 p. 176_1437

Where is time lost in the BMX SX gate start? (presentation)

Grigg, J., Haakonssen, E., Bootes, W. & Keogh, J. W. L. 24 Nov 2017 Australian Skill Acquisition Network Conference, Brisbane, Australia 24-26/11/2017

Validity and Reliability of a 2D kinematics method for measuring athlete symmetry during the BMX gate start (poster)

Grigg, J., Haakonssen, E., Rathbone, E., Orr, R. M. & Keogh, J. W. L. 23 Jul 2017 International Society of Biomechanics 2017: Congress XXVI, Brisbane, Australia, 23-27/7/2017

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In completing this thesis, I would like to acknowledge the time and patience given by all my supervisors. They have all been more than generous with their time and expertise and I could not have completed this project without them. Secondly, I would like to thank Wade Bootes, CA BMX coach, and the athletes who climbed up the stairs to the top of the 8 m ramp again and again to ride down in front of the cameras. Finally, none of this journey would have been possible without the love and support of my husband James.

Ethics declaration

The research associated with this thesis received ethics approval from the Bond University Human Research Ethics Committee. Ethics application numbers RO1913 and 16165.

Author's confirmatory statements

The opinions expressed in this study are those of the author and do not necessarily reflect those of Bond University or Cycling Australia.

Contents

Chapter 1: Introduction

1. Introduction

Bicycle Motocross, commonly known as BMX, has emerged from the field of extreme sports and is now included in the Olympic Games. In the 2008 Beijing Olympic Games, where BMX Supercross (SX) racing was first included in the Olympic Game's list of sports, Australia entered more competitors than any other nation and achieved two 6th placings. This success of the Australian team was built upon in 2012 at the London Olympic Games where Caroline Buchanan placed 5th in the women's event and Sam Willoughby won a silver medal in the men's event. In the 2016 Rio de Janiero Olympic Games, Australian participants won both the men's semi-finals, however they failed to gain a medal in the final event. Currently Cycling Australia (CA) is preparing athletes for the 2020 Olympic Games to be held in Tokyo.

This program of research is the result of a collaboration between Bond University and Cycling Australia's BMX program (formerly BMX High Performance Unit (HPU). During this period of research, the CA BMX coach was Mr Wade Bootes. Mr Bootes was supported by CA Senior Physiologist, Dr Eric Haakonssen. While some organisational restructuring and renaming has taken place during the period of this PhD project, for ease of reference CA's BMX program will be referred to as BMX HPU throughout the thesis. Developmental athletes were supported by BMX Australia (BMXA) and for ease of reference, this group will be referred to as the BMXA Development Academy (BMXA DA). Both BMX HPU and BMX DA organisations worked to support the athlete pathway and were funded, in part, by the Australian Sports Commission (ASC).

1.1 Brief history of BMX

BMX was developed in the 1960s in the USA as an alternative to motor cross, or dirt bike racing [1]. The first BMX tracks were inspired by motor cross tracks. The bicycles were adapted into a new shape to suit the terrain, and a subculture grew around this new form of cycling. BMX racing and BMX freestyle became competitive sports throughout the 1980s and gained a greater following via the medium of the newly created XGames which was designed for television broadcast. In the 1990s, BMX was one of the fastest growing sports amongst youths aged 12-24 years [2, 3]. Historically, BMX racing has existed outside of the mainstream sporting world [1]. In recent years however, this ‘lifestyle sport’ has entered the traditional domain of mainstream sport, with BMXA having over 19,000 active members in 2018 [4].

Between 2014 and 2019 the BMX group within CA was based at the Australian Institute of Sport (AIS) facility on the Gold Coast and was managed by CA with financial contribution from the ASC. CA supported male and female senior elite athletes capable of achieving results at Union Cycliste Internationale (UCI) BMX SX World Championships, World Cups, and the Olympic Games.

1.2 UCI BMX SX racing

BMX SX racing is a distinct format of BMX racing with SX tracks distinguished by the 8 m high start ramp. The UCI oversees a series of races around the world that form the UCI BMX SX World Cup Series. Points and rankings are awarded to individuals for performance in competitions. Cash prizes are offered and sponsorships from bicycle and equipment manufacturers are available, as well as offers from industry funded teams which provide sponsorship in the form of equipment, expenses and sometimes cash rewards and bonuses.

There are two types of race bike categories in BMX, each distinguished by their wheel size. The most commonly used race bikes have wheel diameter of 20” while the cruiser class bikes use a 24” diameter wheel. The 20” wheel is used in all BMX SX events including the Olympic Games. Clothing, safety equipment including helmets, and front plates are all regulated by the UCI [5].

The BMX SX ramp is 8 m high and 10 m wide as per Figure 1-1. While start ramps vary subtly, the initial gradient is approximately 18° until the kink at ~ 3 m where it changes to ~ 28° (see Figure 1-1). Tracks range in distance from 300 – 400 m [6]. The track consists of straights, pump sections, and berms (U-shaped corners) as shown in Figure 1-2 [7]. The common competition format starts with motos: three races in heats of up to eight racers depending on the number of entries. At the end of motos the top four placed riders from each moto go to the next round of finals (16 or 8 finals depending on the number of entries). Lane selection in finals is based on lap times from the previous race. Athletes recording the best times get preferred lane selection in a similar process to swimming finals [5].

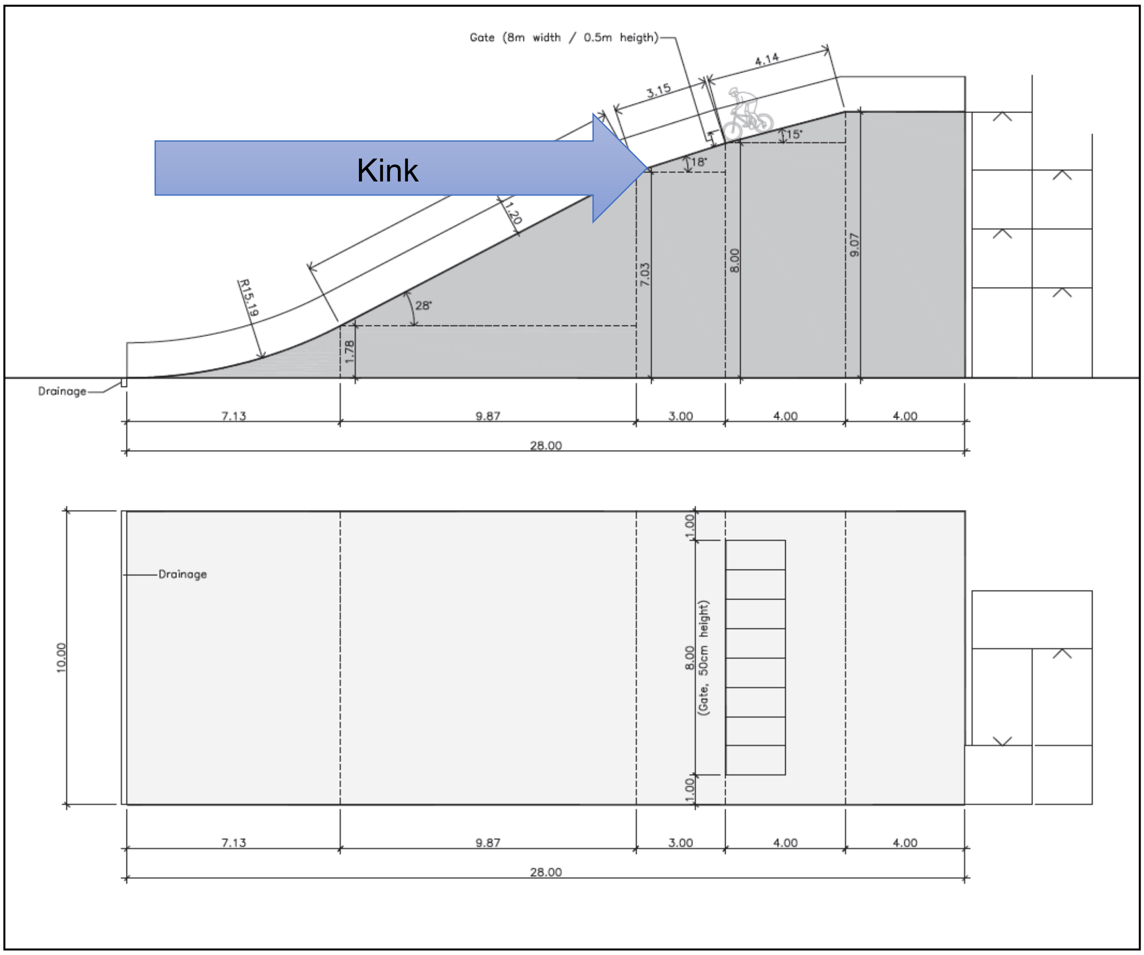

Figure 1-1. 8 m ramp design specifications adapted from BMX Track Guide (page 20), by UCI, 2014, Switzerland. Copyright (2014) by the UCI

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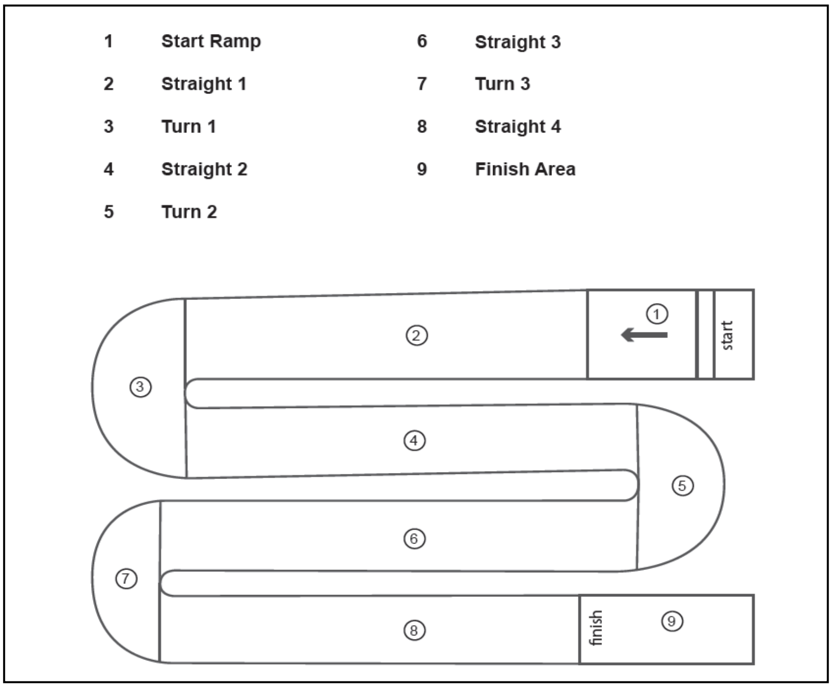


Figure 1-2. Elements of a SX adapted from BMX Track Guide (page 5), by UCI, 2014, Switzerland. Copyright (2014) by the UCI.

Individual Olympic Game qualification is based on race results in the race calendar year before an Olympic Game's year. Nations can qualify a maximum number of 2 males and 2 females for the Olympic competition depending on their nation ranking during the qualification period. The Olympic competition format follows the aforementioned UCI BMX SX competition format [8].

At the commencement of this program of research there was only one Olympic standard SX track in Australia which was based at Sleeman Sports Complex in Brisbane. This was where data collection took place. Subsequently, an Olympic standard track has been built in Bathurst, New South Wales, Australia.

1.3 Categorisation of riders

Whilst BMX HPU and DA riders were all international competitors, they were categorised into groups according to performance for the calendar year when data was collected. These groups were devised in consultation with the BMX HPU and with reference to other groupings used within cycling research [9]. All athletes in these groups were 16 years of age or older.

World Class: Podium
All of these athletes had achieved a 1st, 2nd or 3rd placing in a UCI World Cup or World Championship event in the 12 months preceding the date of the trial.

Elite: Semi for Women, Quarter for Men
All of these athletes had progressed to semi-finals for women and quarter finals for men in an UCI World Cup or World Championship SX event in the 12 months preceding the date of the trial.

All of the athletes who participated in the studies that formed this PhD project were in the DA or HPU and have attended at least one UCI World Cup or World Championship SX event in either Elite or Junior class (under 18 years of age) in the 12 months preceding the date of data collection.

1.4 The bike

A BMX bike has a distinct look, dimensions and manoeuvrability. There are slight differences between BMX bikes adapted for specific use as shown in Figure 1-3. The racing bike has narrower wheel rims and a slightly longer wheelbase than other BMX bikes. The 32 spoke wheel adequately withstands the jump landing loads in an SX race but is not strong enough for landing loads associated with freestyle tricks. Rather than the typical U-brakes, racing bikes only have rear brakes which provide the stopping power needed for a SX bike at speed.

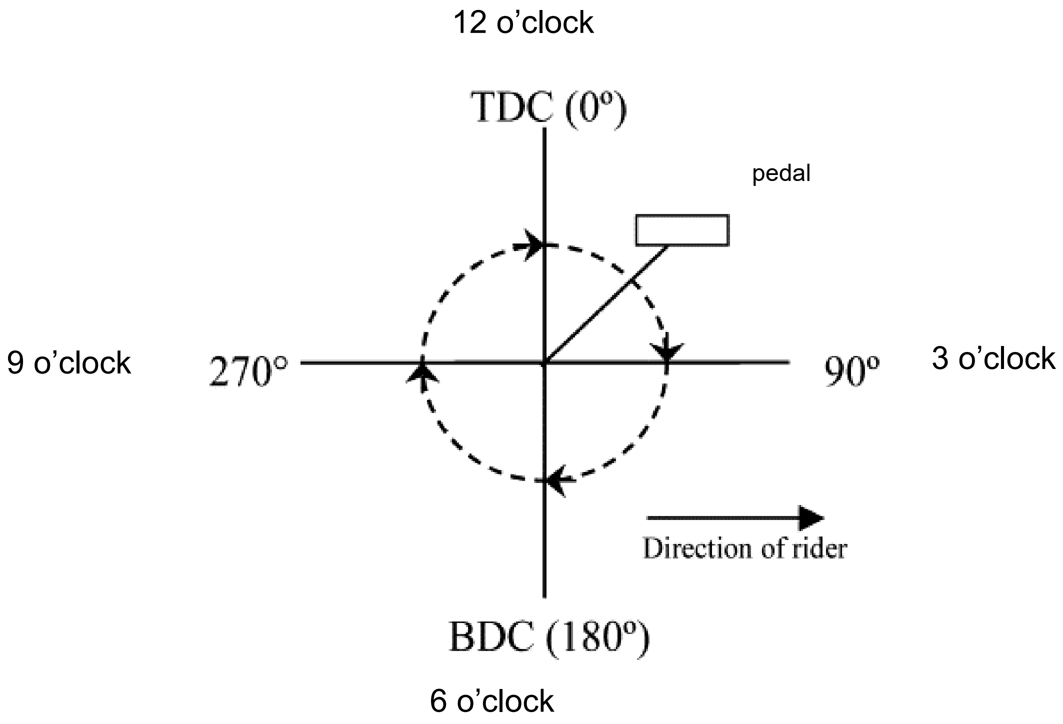
Figure 1-3. Different BMX types. Reprinted from "10 Tips for Buying a Complete BMX Bike", In BMX Transworld, Retrieved August 21 2015, from http://cdn.bmx.transworld.net/files/2009/09/1-bike-types.jpg.

The racing bike, which is depicted in more detail in Figure 1-4, has a lighter frame than other BMX bikes and is made from carbon fibre or aluminium as it is designed for speed rather than strength. The top tube (TT) of the frame is 19-22" long and for SX races the wheel diameter must be 20". Taller riders prefer a longer TT. Other dimensions such as the head tube length can vary slightly, however racing regulations result in a high degree of homogeneity between bikes. The largest variation between riders comes in the selection of the crank length, the front and rear cog (i.e. gearing selection) and tyre selection.

Figure 1-4. Components of a BMX bike. Reprinted from “10 Tips for Buying a Complete BMX Bike”, In BMX Transworld, Retrieved August 21 2015, From http://cdn.bmx.transworld.net/files/2009/09/1-bike-types.jpg.

1.5 Crank action

In this thesis, the movement of pedalling is described as the *crank action*. Figure 1-5 shows the trajectory of the foot and pedal in relation to the pedal axle. It is considered to start at top dead centre (0°) and progress around the circle in the direction of bike movement. In BMX SX, the starting leg is positioned around the 3 o'clock position so the first crank event is from 3-12 o'clock. The second crank event starts at the 12 o'clock position. Different researchers have used different nomenclature, but the degrees of rotation and clock face terminology are the most common [10].



TDC – Top dead centre

BDC – Bottom dead centre

Figure 1-5 Crank action.

1.6 The gate start

BMX racing has a unique start procedure. Eight riders line up behind the gate in lanes. A standard warning is announced: “Ok riders, random start, riders ready, watch the gate”. Following the word “gate”, there is a random delay of 0.1 to 2.6 s followed by a sequence of four rapid tones that coincide with a series of red, yellow, yellow and green lights. The gate falls on the last tone and light.

Riders and coaches agree that a competitive advantage is gained by being ahead of the field at the bottom of the ramp, preferably at the kink. In his online coaching blog, Greg Romero who coached Olympic medal winners Jill Kintner and Mike Day, talks about the importance of training for optimal mechanics at the start in order to gain a competitive advantage [11]. Researchers have also focused on this part of the race as they observe that the first rider to the base of the ramp is able to pick the most advantageous line through the next section and is better able to avoid collisions with other BMX racers [12-14].

A study investigating placings using four time splits during four World Cup events (Canada, Holland, Norway and USA) examined the relationship between the position of the rider at the first split and their finishing position [5]. The time at the first split was on average 1.075 ± 0.816 s which corresponds to a position on the ramp. A Kendall's τ_b bivariate correlation was performed to identify correlations between placings at the first time split and finishing positions. A statistically significant correlation was found between riders in the 1st, 2nd and 3rd placings at the first split and in the 1st, 2nd and 3rd placing at the end of the race ($\tau = 0.59$, $p < 0.01$). This means that there is a moderate positive correlation between being in the first three at the first timing split (on the ramp) and in the first three at the end of the race [5]. As the top four riders in the qualifying rounds go through to the next round, the importance of being in the top four riders at the end of all races is critical, and this correlation to position early on the ramp highlights the importance of optimising gate start performance.

1.7 Deterministic model of the BMX gate start.

A deterministic model shows the contributing components to performance of the action [15]. The model shown below in Figure 1-6 was developed by Gross et al (2017) and considers the BMX starting performance to be the time to the base of the ramp [16]. The starting point of the Gross deterministic model is with the development of velocity. This is then broken into initial velocity, distance and acceleration. The impact of the ramp slope is considered which is an important factor in BMX starts as the incline of the ramp can vary from ramp to ramp. Equipment is considered as part of 'air and rolling resistance'. This needs to consider rollout factors such as tyre (thickness and tread) and ramp surface. Gear ratio is considered as part of pedalling power, however crank length also needs to be considered because of the impact on torque. While acceleration before and after 'gate opens' is considered, the navigation of the gate is not specifically considered. This is important as is the stimulus for lifting the front wheel.

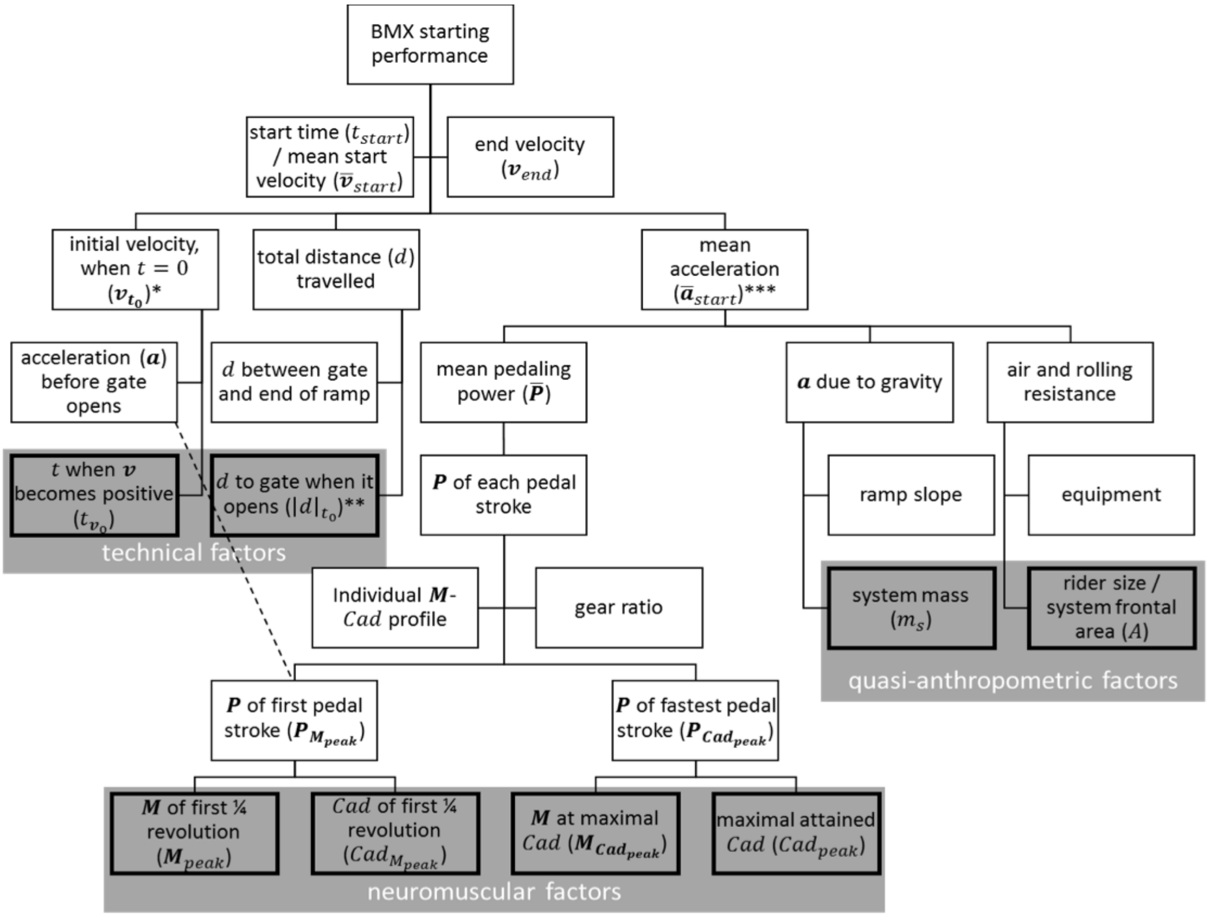


Figure 1-6 Deterministic model presented by Gross et al 2017 [16]

The model presented in Figure 1-7 has been developed for this thesis. Unlike the Gross model, it uses kink time as the gate start performance measure as this is the performance measure referenced throughout the thesis. The kink time split incorporates the gate start action and first three cranks which, as discussed further in Chapter 2, have been shown critical to gaining optimum position on the track. The gate start performance is then a combination of the reaction time, development of power and the navigation of the falling gate. If one or other of these factors are not executed the action will fail. The development of power starts with a reaction to the stimulus. If is a combination of the application of torque and the development of cadence, that is turning the cranks over as quickly as possible. Study 3 (Chapter 6) investigates reaction time to investigate the trainability of this component in the particular setting of the BMX gate start. The other studies in the thesis investigate body position and movement development, which are both kinematic studies. These two determinants are critical for development of force and navigation over the gate, and thus are worthy of investigation.

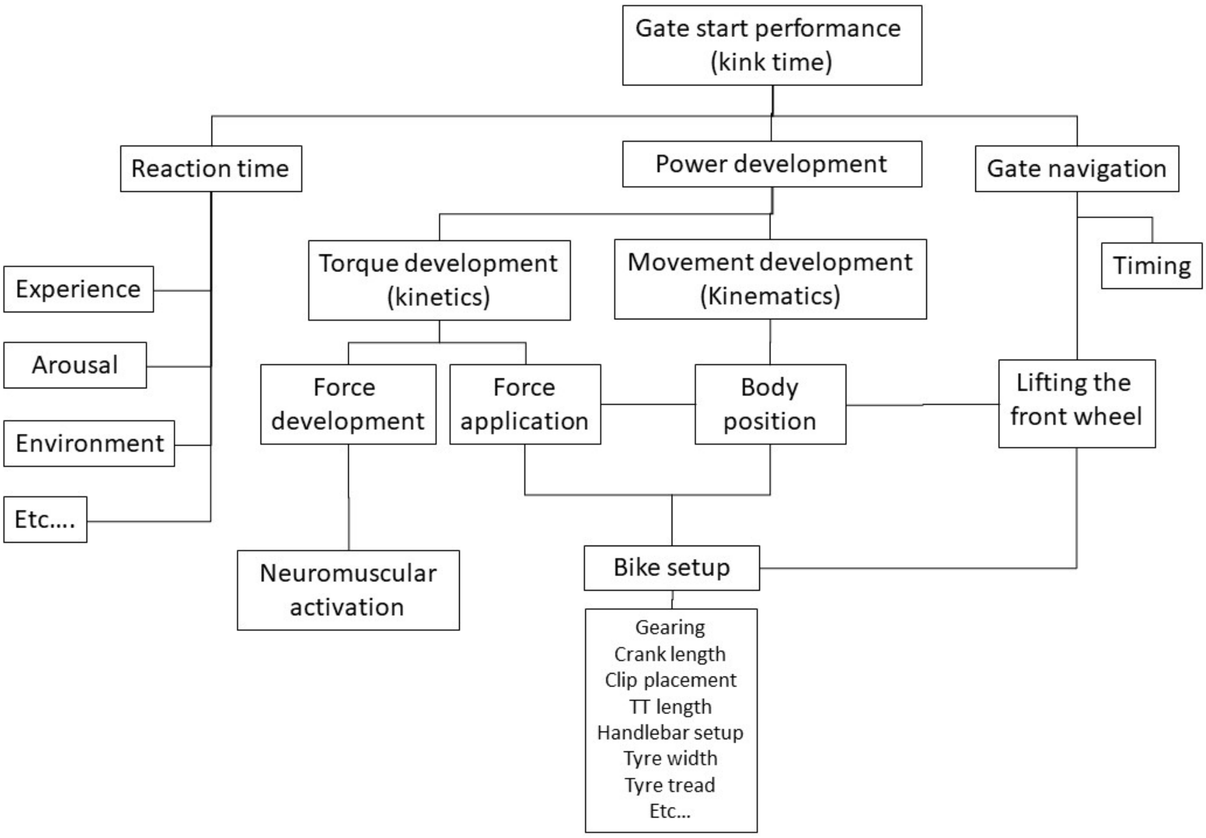


Figure 1-7 Determinant model using kink time as the gate start performance parameter

1.8 Biomechanics

Biomechanics is the study of the interaction of forces and biological structures, that is, the forces that act within and on a body, and the resulting motion [17]. Kinematics is a subset of biomechanics that describes the geometry of motion [17]. It is used to qualify visible movement in terms of actions such as flexion/extension, movement rate such as velocity, and displacement such as angular range of motion about a joint [18]. Such measures are commonly described as movement characteristics.

The holy grail of sports biomechanics is to describe the “ideal technique” for optimal performance. Chaos theory suggests that in any dynamic system there is an attractor state which is the point of greatest compromise between efficiency and efficacy [19]. By looking at the attractor states of elite riders, an understanding of how they generate a high level of performance can be gained. Study of movement variability around this “ideal technique” can inform as to which movement characteristics are modified to accommodate contextual interference. Comparing the movement characteristics of World Class riders to those of Elite riders may help to explain the difference in performance between the two groups.

1.9 Existing BMX research

BMX research began in the 1980s with a focus on injury mechanisms and prevention [19-22]. The next areas of interest to researchers were the sociological context of the BMX subculture [2, 23-25], track design [24] and the bike itself [13, 26, 27]. With the inclusion of BMX in the Olympic Games, performance focused research increased with studies examining performance tools [28, 29], key components of a BMX race, physiological demands and characteristics [30] as well as skill acquisition and biomechanics [5, 12-14, 27-29, 31-44]. Preliminary studies have investigated the biomechanics of the BMX gate start [16, 38, 45], however, it has been suggested that these studies do not relate to coachable performance factors [14]. It must also be noted that some of these studies did not use a standard SX gate start format [16, 36, 40] and were limited in participants (1-9) and trials analysed (1 per participant). Noting the importance of the gate start to athlete performance and concerns regarding the lack of pragmatism in previous research investigating BMX gate starts, the series of studies in this thesis sought to address this gap.

1.10 Interactions between science and coaching

Studies have shown that sports coaches build their knowledge from a variety of sources from personal experience to formal education such as university degrees or sport specific training courses [46]. Australia has been at the forefront in recognising the importance of formal coaching qualifications and supporting coaches with ongoing professional development and education opportunities [46, 47]. Coaches also rely heavily on personal experience and discussion with fellow coaches [46] which increases available knowledge from which to base a coaching approach and inform decision making. In highly structured activities such as in a game of chess, situations such as opening gambits can be precisely repeated in future games and results determined [48]. In BMX however, there are many variables that may change from race to race. For example, each athlete has a somewhat different anthropometry, bike setup and preference for either watching the start lights or listening to the start tone, they may start in different lanes and each track is slightly different. While a BMX coach's empirical knowledge is invaluable, evidence obtained through scientific research may help to inform BMX coaches and augment their decision-making ability.

The researcher worked with CA Senior Physiologist, Dr Eric Haakonssen and CA BMX Coach, Wade Bootes to develop a list of spatiotemporal parameters that the Australian BMX athletes and coaches experientially believe to be critical to gate performance. This collaboration pooled the experience of Mr Bootes, Dr Haakonssen and the research process to validate the experiential information currently being used for coaching, and to produce objective data which can be used to refine coaching guidelines and provide a stronger evidence-base to improve BMX athlete performance.

Mr Nick Flyger's (Head Coach, CA Track Sprint) research with CA in the area of track sprint cycling has involved a similar process of ongoing coach and sport scientist consultation which has led to improvements in the coaching and biomechanical analysis of the Australian track sprint cycling program. Mr Flyger has been involved as a consultant for this project and is enthusiastic about its potential to inform BMX coaches, particularly with a focus on 2020 Tokyo Olympic bound athletes.

1.11 Thesis overview

The overall objective of this program of research was to investigate the movement characteristics of the BMX SX gate start action of World Class and Elite athletes relative to kink time to better inform the coaching, sports science and strength and conditioning of BMX athletes. In a sport such as BMX riding when there is so little literature that the potential for research is almost boundless, this made it quite difficult to put limits on the research project as there were so many valuable and interesting questions that could be addressed, however it was necessary to start at the beginning. In biomechanics this is kinematics. Kinematics describe ‘what is happening’ by measures of time, displacement, velocity and acceleration in both linear and angular motion. Studies 1,2 and 5 use kinematics to answer the ‘what’ question. While the ‘why’ questions that focus on the kinetics of a successful gate start are valid and important, they has been left to whoever comes next. Kinetics involves the identification of the centre of mass (CM) of riders with helmets and the bikes and the interaction with this and the location and timing of the application of force. Such a study was beyond the scope of this PhD project.

The first step toward meeting this objective was a review of the literature. The results of the literature review informed a series of research studies with pragmatic real-world suggestions to improve BMX athlete performance. Three observational, one methodological and one intervention study were completed and presented in this thesis in manuscript format. The major findings were summarised in the brief conclusion at the end of the document.

Two sections of the thesis have been published (Literature review: Kinematics of the BMX SX gate start, and Validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX SX gate start) and one has been accepted for publication as a book chapter (Determinant phases of the BMX SX gate start action). Permission to reprint each of the published and accepted manuscripts has been gained, with this presented in the Appendices (Appendix 1, 2 and 3). In accordance with the conditions to reprint imposed by the publishers, no alterations to the text have been made, with the exception of figure and table numbers. This means that there is some repetition of figures and contextual and methodological explanation, including abbreviations throughout the thesis. In view of the nature of this research and the way in which it may be accessed by the target audience of both researchers and those involved in the sport of BMX, the study chapters have been written to stand alone as opposed to referencing previous chapters for information pertaining to methodology etc. The published chapters are referred to in their published form where applicable.

Figure 1-8 shows the outline of the thesis. The literature review was divided into two main components: narrative contextual review and methodological review. The five studies were divided into two methodological sections, the first being motor control based (Studies 1, 2 and 3) and the second biomechanical (Studies 4 and 5). The motor control studies set the basis for the subsequent studies as they divided the action into components (phases) allowing for a preliminary understanding of the action and its determinant subcomponents. The biomechanics studies deconstructed the BMX gate start action in order to understand what described a ‘fast’ gate start. The individual studies that make up the research project were outlined below.

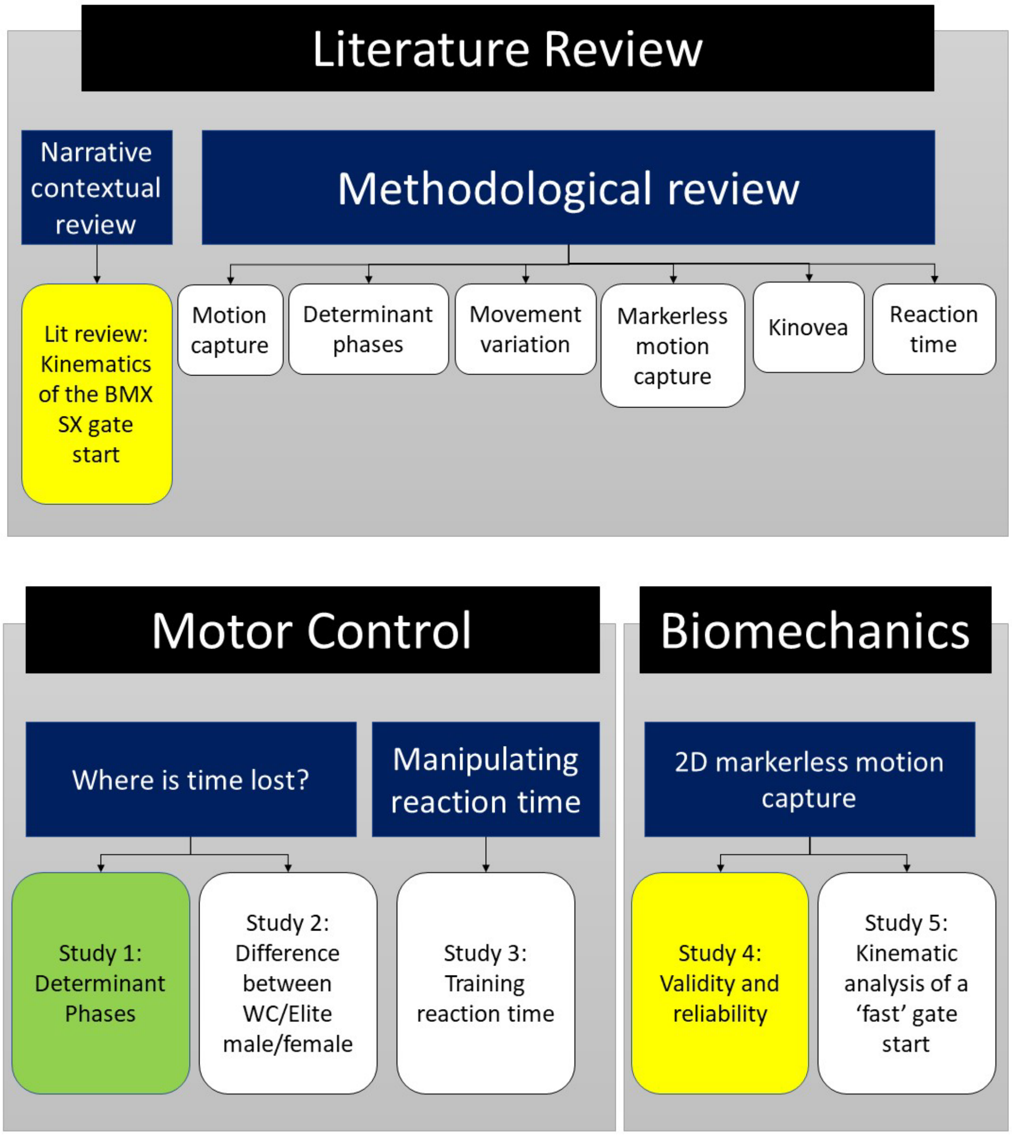


Figure 1-8 Thesis overview. Yellow cells denote published articles and the green denotes accepted for publication

To establish known research in this field and identify gaps in the research, an initial review of the literature was conducted (Chapter 2). The focus of this review was the literature on BMX racing, cycling, biomechanics and motor control, with key words entered into dedicated databases to capture relevant research for synthesis. The focus and subsequent search terms were kept relatively broad due to the infancy of this sport and potential lack of dedicated research in this field.

Study 1 (Chapter 4) sought to determine whether the BMX gate start action could be described by a number of component phases and whether these phases were invariant within and between athletes, in accordance with Schmidt's Schema Theory [49]. The natural follow on question was 'can we use these phases to find out what is different between WC and Elites, and if there is a gender-based difference?' This question formed the basis of Study 2 (Chapter 5).

Study 2 used the phases defined in Study 1 to describe the gate start performance of 10 athletes, five WC and five Elite, of which six were male and four were female. The difference in relative and absolute time between WC/Elite athletes and between males/female athletes was examined for each phase. The difference in variation in absolute time for each phase was also examined to determine whether WC/Elite or male/female were more consistent in their movement through the phases of the BMX SX gate start.

Study 3 (Chapter 6) was an intervention study aiming to determine whether training could reduce the reaction time on the gate start with an off-track training protocol. The initial reaction to the start stimulus is the very first part of the race and is thought to be relatively unrelated to muscular strength/power or riding technique. Nine participants were recruited to either a control (*n* = 5) or an intervention (*n* = 4) group. A short reaction time training protocol using a bespoke pedal device was performed each day for two weeks. Pre and post testing on the reaction training device and on the SX gate were used to determine the efficacy of the training and potential transfer to a reduction in kink time.

Study 4 (Chapter 7) investigated the validity and reliability of the 2D motion capture methodology and kinematic analysis to be used in Study 5. The methodology tested in Study 4 allowed for in situ data collection on the BMX SX ramp without interfering with the athletes, ramp or training sessions. This enabled an ecologically sound data collection methodology for use in Study 5.

Study 5 (Chapter 8) used the methodology tested in Study 4 to collect kinematic data for 5 trials for each of the 14 athletes. This was then analysed in reference to kink time in order to identify characteristics of a fast gate start.

Chapter 9 of the thesis manuscript is a discussion of the relevance to this PhD research in respect to the current literature in the field of BMX racing, its relevance to BMX coaches and athletes, major findings, limitations of the project as a whole and suggested further areas of research. The final chapter (Chapter 10) of the thesis is a very brief bullet point synopsis of the findings of the research project.

Chapter 2: Review of literature pertaining to the PhD

2. Review of literature pertaining to the PhD

This chapter details a review of the literature as a means to underpin the program of research undertaken in this PhD. The initial literature review focussed specifically on the current state of research within the field of BMX racing. Acknowledging that research in the area of BMX racing was limited, a further broader search was done to examine relevant literature in other cycling modalities that could be used to inform the thesis. Literature relating to key concepts and methodologies used in the thesis such as markerless motion capture, reaction time and determinant phases were reviewed before examining the gaps in the BMX SX literature and where this thesis will sit in relation to the current state of research.

2.1 Literature review: Kinematics of the BMX SX gate start

2.1.1 Preface

This chapter is derived from an article published in Journal of Science and Cycling on 18 May 2017 available online: http://www.jsc-journal.com/ojs/index.php?journal=JSC&page=article&op=view&path%5B%5D=249.[1]

Grigg, J., Haakonssen, E., Orr, R. M., & Keogh, J. W. L. (2017). Literature review: Kinematics of the BMX SX gate start. Journal of Science and Cycling, 6 (3-10).

The following literature review outlined the state of research in the area of the biomechanics of BMX racing as at the time of journal article submission, April 2017. As additional research in this area has occurred following the publication of the article, an addendum has been added (§2.1.8) to include relevant additional research published post article submission and prior to thesis submission. Permission has been granted to reprint the article in this thesis in the accepted manuscript formatting (see Appendix 1). The formatting of the references retains that required for publication as requested by the publisher.

2.1.2 Abstract

The aim of this literature review was to identify the depth and scope of peer reviewed literature on rider kinematics of the Bicycle Motocross Supercross (BMX SX) gate start action, in particular literature that describes the optimal BMX SX gate start technique or relates to the prescription of training methods to improve performance. A pilot search was conducted to identify the optimal databases to use. Key search terms and inclusion and exclusion criteria were applied to select the articles of relevance which were then critically analysed using the Quality Assessment Tool for Observational and Cross-Sectional

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[1] This statement is required by publishers as a condition of reproduction in the thesis.

Studies. Two studies were retained for review. Both the studies were limited by number of participants and methodological rigour and scored poorly on the Quality Assessment Tool for Observational and Cross-Sectional Studies. No studies were found that correlated kinematic measures from the gate start action to gate start performance outcome. A secondary aim was to investigate the tactical importance of the gate start, power generation at the start of a BMX race and skill acquisition. Literature reported discrepancies between field and laboratory results which demonstrates the importance of ecologically valid research methodology. Despite evidence that the gate start is a critical component of the race with direct implications for race outcome, this review of the literature identified very limited research in the area of BMX rider kinematics of the BMX SX gate.

2.1.3 Introduction

Bicycle motocross (BMX) was developed in the USA in the late 1960s as an alternative to motocross (Nash 1986). The first BMX racing tracks were inspired by motocross tracks and the bicycles were adapted into a new shape to suit the terrain. Throughout the next decade a new subculture formed around this novel form of cycling. BMX racing and BMX freestyle grew in popularity as competitive sports throughout the 1980s and gained a greater following via the medium of the newly created X Games (Nash 1986). In the 1990s, BMX was one of the fastest growing sports amongst youths aged 12-24 years (Honea 2013; Nelson 2010). While BMX racing has traditionally existed outside of the mainstream sporting world, in recent years this ‘lifestyle sport’ has entered the domain of mainstream sport (Nash 1986).

Academic BMX research began in the 1980s with a focus on injury mechanism and prevention (Brøgger-Jensen et al. 1990; Illingworth 1985; Stathakis 1997). Further areas of interest to researchers included the sociological context of the BMX subculture (Edwards and Corte 2010; Honea 2013; Rinehart and Grenfell 2002; Scott and Shafer 2001), and the bike itself (Manolova et al. 2010; Mateo-March et al. 2014; Mateo-March et al. 2012b).

With the inclusion of BMX in the 2008 Beijing Olympics, the profile of BMX Supercross (SX) racing rose and performance related research increased with studies into performance measurement tools such as power meters (Bertucci et al. 2013; Chiementin et al. 2013; Costa 2013), key components of the BMX race such as pumping and pedalling (Cowell 2011; Rylands et al. 2016a), physiological and psychological demands (Herman et al. 2009; Louis et al. 2013; Marquet et al. 2015; Mateo-March et al. 2012a; Mateo et al. 2012; Zabala et al. 2011; Zabala et al. 2008), skill acquisition (Zabala et al. 2009) and biomechanics including power generation, the difference between laboratory and field results, and rider kinematics (Bertucci and Hourde 2011; Bertucci et al. 2007; Chiementin et al. 2012; Gianikellis et al. 2011; Mateo-March et al. 2012b; Rylands et al. 2013; Rylands et al. 2016b; Rylands et al. 2016c; Zabala et al. 2009).

The start of the BMX SX race is critically important and has been shown to relate directly to race placings (Rylands and Roberts 2014). It is performed using a specific start protocol and start ramp design as directed by Cycling's governing body, the Union Cycliste Internationale (UCI) (Union Cycliste Internationale 2014b). The Olympic standard SX tracks have an 8 m high ramp with initial gradient of ~18° which changes to ~28° at ~3 m. The location on the ramp where this angle change occurs is often referred to as the 'kink' and is shown in Figure 2-1. Leading the race early enables a rider to pick the most advantageous line into the first jump (Mateo-March et al. 2014; Mateo et al. 2011; Zabala et al. 2009). Coaches and riders focus a large proportion of training time on improving the gate start action. This occurs not only at the track, but also by supplementing with gym based strength and power training movements that are believed to be functionally similar to the gate start action (Cowell et al. 2012a). Given the tactical importance of the race start, there is value in examining the rider kinematics of the gate start action and their relationship to performance in this key phase of the event. Enhancing knowledge of the optimal gate start action will guide coaches to provide valid technical feedback and may aid in the prescription of more functionally appropriate gym based training methods.

The aim of this literature review was to identify the depth and scope of peer reviewed published literature on rider kinematics of the BMX SX gate start action. Literature on the tactical importance of the gate start, power generation and skill acquisition were reviewed as a secondary aim because of their importance to coaching and training.

2.1.4 Search method

A pilot search was conducted in AUSport, SPORTDiscus, ProQuest, GoogleScholar, Google, PubMed and Scopus to identify where suitable literature was most likely to be listed. Search terms were ‘bmx’ OR ‘bicycle motorcross’ OR ‘bicycle motocross’ AND ‘cycling’. Adding the search term ‘biomechanics’ proved too restrictive in the pilot search as many studies in this area did not use this term as a key word or include it in the text. The term ‘bicross’ used in some European countries to refer to BMX racing did not yield any further results. Based on the number of returns from the pilot search, it was decided that SPORTDiscus, ProQuest and Scopus were the most suitable databases to search. Figure 2-2 outlines the review process. Further to the database searches, a search in Google Scholar was performed. Reference lists of retained articles were also reviewed for further relevant literature and a forward search was performed to identify any articles that cited the studies included in the review. All identified records were imported into Endnote and the duplicates were removed. The inclusion and exclusion criteria as outlined in Table 2-1 were applied. The quality of studies relating to rider kinematics were assessed by two assessors using the NIH National Heart, Lung, and Blood Institute: Quality Assessment Tool for Observational and Cross-Sectional Studies (National Institute of Health USA 2014). Studies that provided valuable information for contextual background were retained and discussed.

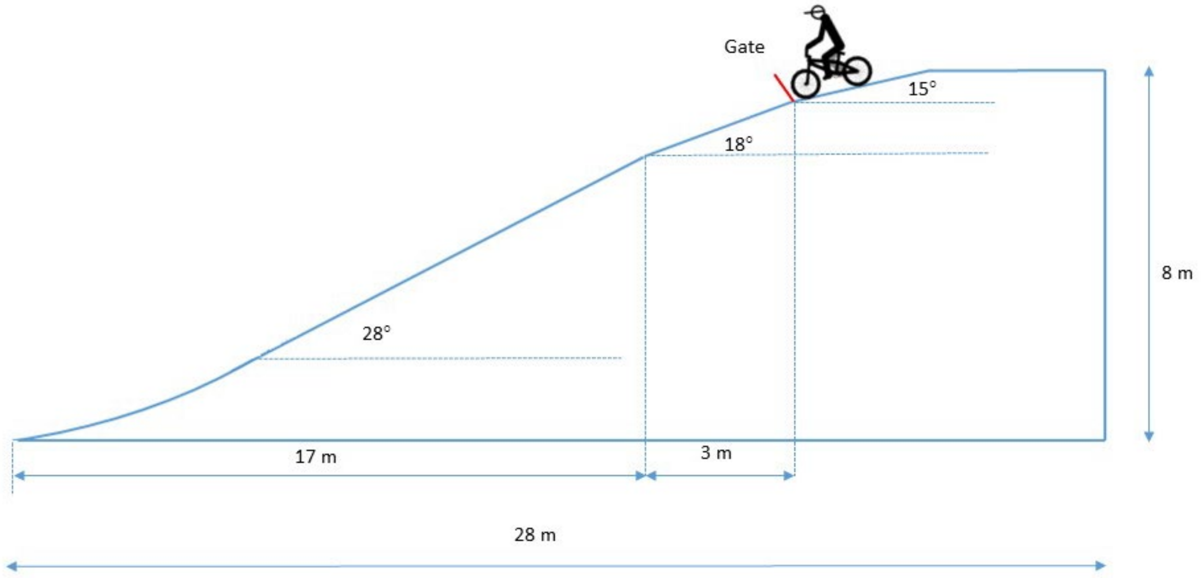

Figure 2-1 Supercross ramp design as specified by the UCI BMX Track Guidelines (Union Cycliste Internationale 2014a). Schematic not to scale.

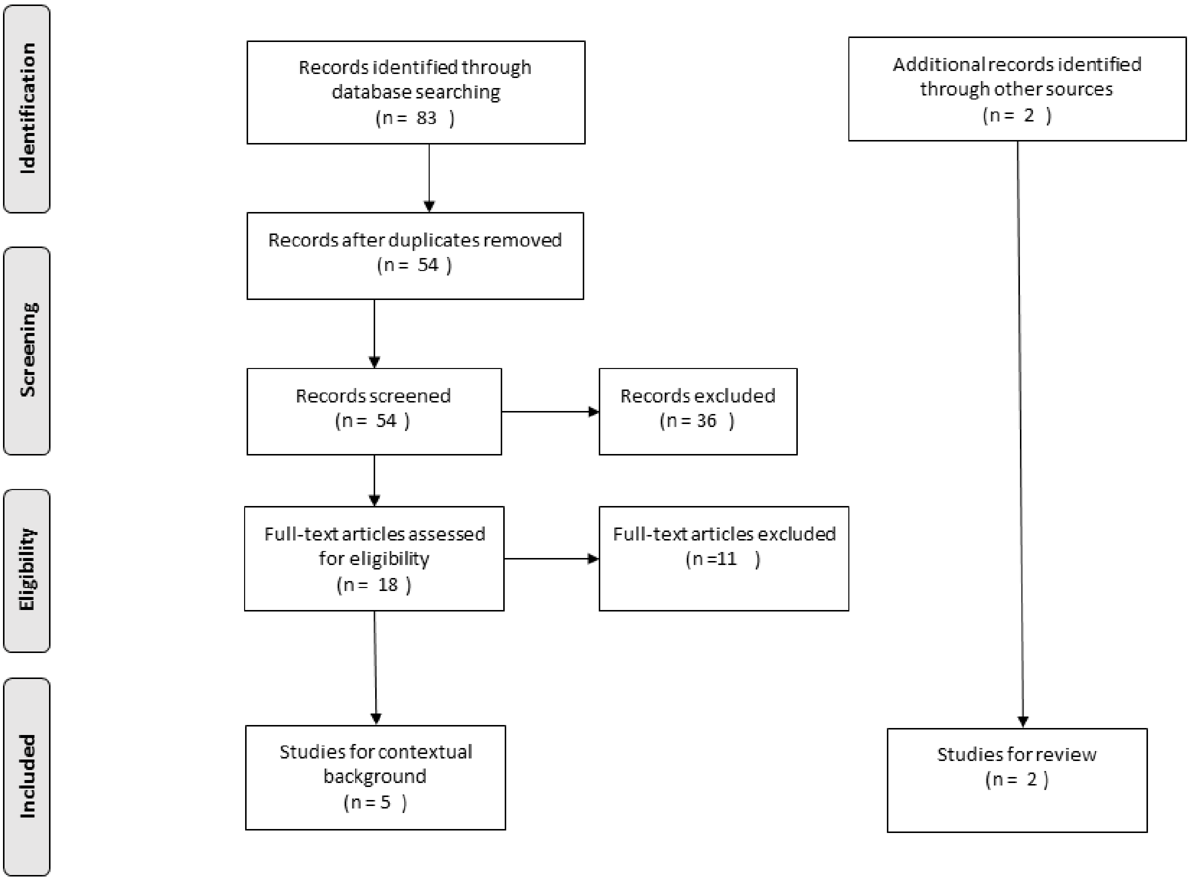

Figure 2-2 Search process flow chart

Table 2-1 Areas of research to be included in the literature for inclusion

Inclusion criteria	**Exclusion criteria**
BMX cycling power generation	Not related to BMX racing, e.g. BMX freestyle
Gate start technique	Duplicates
BMX race start tactics	Not published in an academic journal
BMX race coaching methodology	No English translation available
BMX cycling biomechanics	

Table 2-2 Literature on the kinematics of the BMX gate start. NR = not reported

Author Date	Main Aim	n	Setting	Kinematic parameters	Trials	Equipment	Validity and reliability of methodology	Statistics	Finding Summary
Gianikellis, Skiadopolous & Bote (2011)	Evaluate gate start technique of three riders and examine influence of individual characteristics	3 int Gender – NR Age – NR Training – NR Mass – NR	Training track 20º slope	Displacement (m) Velocity (m/s) Joint Angle (°) Segment Angle (°)	Number performed - 5 Fasted 1 reported	2 S-VHS video cameras (Panasonic AG-DP800H, AG-DP200E) Frame rate – 50 fps Kinescan/IBV 3D video photogrammetry system (version NR) Markerless 28 digitised points (bike and rider)	NR	All information reported per participant. No summary information	Preliminary study only. Each rider had their own individual technique and should be coached accordingly
Kalichová et al. (2013)	Describe dominant movements throughout defined phases of the gate start in a small sample – pilot study	2 int 1 male 1 female Age – 21,22 Training – 14, 14 years Mass – 88, 65 kg	NR	Temporal (s) Joint Angle (°) Joint velocities (m/s)	Number performed -NR Fastest 1 reported	2 Camera (not specified) Camera placement NR Frame rate – 100fps SIMI Motion software (version NR) Reflex marks (sic) 7 markers (rider)	NR	All information reported per participant. No summary information	Preliminary study only. Gate start action defined in 5 distinct phases each with distinctive kinematics

Table 2-3 Significant literature on the BMX gate start.

Author Date	n	Discipline	Outcome Measures	Design	Finding
Bertucci (2011)	9 int 17 nat	Physiology	Vertical jump (cm) Sprint cycling test (W; W/kg) Wingate test (W; W/kg)	Cohort - descriptive	Correlation existed between squat jump, countermovement jump, seated sprint test, standing sprint test, seated Wingate test, and standing Wingate test.
Cowell, McGuigan & Cronin (2012)		Strength and conditioning		Educated opinion	Recommended strength training exercises for BMX riders with a focus on appropriate rate of force development.
Mateo, Blasco-Lafarga & Zabala (2011)	9 int	Biomechanics Physiology	Cycling power at the pedal (W) Bike speed (m/s) 3 different types of race tracks	Cohort - descriptive	Peak pedalling power as measured on an ergometer was not matched during gate start, suggesting that application of technique was critical during the start phase.
Rylands et al. (2013)	7 int	Biomechanics Physiology	Peak power (W; W/kg) Velocity at peak power (m/s) Cadence at peak power (rpm) Mean fatigue index where Fi (W/s) = (peak power – minimal power)/time (s)	Cohort - descriptive	In a 50 m sprint test, the BMX riders' absolute (W) and relative (W/kg) peak pedalling power (21.29 ± 0.84 W/kg) were similar to those reported in other sprint cycling disciplines such as track sprint (21.83 ± 0.76 W/kg; [50]. BMX riders fatigued earlier. Once peak power was reached, velocity was controlled by cadence.
Zabala, Sánchez-Muñoz & Mateo (2009)	6 int	Motor learning	Time to 4.5 m from gate start (s)	Cohort – intervention (no control)	Audio-visual and coaching feedback during a gate training session improved gate - 4.5 m time (pre-treatment: 1.264 ± 0.045 s; post-treatment: 1.047 ± 0.019 s). Improvements remained 2 weeks after treatment (1.041 ± 0.021 s). Initial times were 1.264 ± 0.045 s, which reduced to 1.047 ± 0.019 s after treatment and was 1.041 ± 0.021 s in the retention test.

Int = international competitor, Nat = national competitor, rpm = revolutions per minute.

2.1.5 Results

As shown in Figure 2-2, 83 records were returned in September 2016. Kalichová et al. (2013) and Gianikellis et al. (2011) (see Table 2-2) were reviewed according to NIH National Heart, Lung, and Blood Institute: Quality Assessment Tool for Observational and Cross-Sectional Studies (National Institute of Health USA 2014) and were both found to be of 'poor' quality by both reviewers. While Zabala et al. (2009) demonstrated the usefulness of kinematic parameters in the administration of feedback to riders, this study was not included in the primary review as rider kinematics were not reported. Five publications were reviewed as part of the secondary aim relating to tactical importance of the gate start, power generation and skill acquisition (Bertucci and Hourde 2011; Cowell et al. 2012a; Mateo et al. 2011; Rylands et al. 2013; Zabala et al. 2009). These additional five studies are summarised in Table 2-3.

2.1.6 Discussion

The ultimate aim for a BMX rider is to win a race, with the results of Rylands and Roberts (2014) demonstrating a clear correlation between gate start performance and race outcome. While correlations do not necessarily identify causation, the demonstrated relationship between gate start performance and race outcome observed by Rylands and Roberts (2014) justifies further specific examination of the BMX gate start. Research on the gate start identified in this review can be grouped as relating to the kinematics of the gate start action, power generation and skill acquisition. A consensus around the optimal gate start action has not been demonstrated. A study investigating rider kinematics and their relationship to performance outcomes would assess the validity of theories proposed by experienced coaches and riders and may contribute greatly to coaching pedagogy and strength and conditioning programming methods for the sport of BMX.

2.1.6.1 Kinematics of the BMX Gate Start Action

The review process conducted for this study only identified two studies of BMX gate start biomechanics. These two studies described the forward movement of the bike (Gianikellis et al. 2011) and body segment movement (Kalichová et al.

2013) but did not relate findings to coachable quantitative performance factors such as timing splits. While the number of trials performed per rider was more than one, in each study only one trial per rider was reported. No validity or reliability data were referenced for the methodology used in either of these two studies. The first of these studies used an outdoor ramp with a 20° slope and rather than a UCI standard SX ramp as per Figure 2-1 (Gianikellis et al. 2011). This article gives an example of motion capture during the BMX gate start action and a preliminary analysis of kinematics during this action which could be used for further examination of this action. This study was limited by the small number of riders (*n* = 3), number of trials analysed (1 per rider), low frame rate (50 FPS) and the use of only two video cameras to construct the 3-D coordinates for the bike and rider. The digitisation process used 28 markers (21 on the body and 7 on the bike) to rectify a simple free body diagram in 3D.

A key parameter used by Giankellis et al. (2011) to describe the efficiency of the start was the position of the front hub relative to the front edge of the gate at two points in time: the start and when the gate landed flat to the ground. The action was divided into two phases: the start of the rider movement to when the gate starts to move; and the point at which the gate starts to move to when it lands flat to the surface of the ramp. Position, speed and acceleration at the gate landing were reported. The highest bike velocity in the anterior-posterior (horizontal) direction was 12.12 m/s. It was reported that when the gate began to fall, two of the riders were still moving in a backwards direction (-0.17 m/s and -0.55 m/s). In contrast, the rider that was moving forward when the gate started to fall had already reached their highest velocity in the backward direction (-1.95 m/s). This suggests that the aspect of the start action relating to navigating the bike over the falling gate was performed more efficiently by this rider, however the association between the rider action and total ramp time was not quantified. The range of knee flexion for two participants was reported (17° and 18°). It is reasonable to assume that the front leg was the reference leg, although this was not specified. Trunk flexion was reported for one rider as 15.18°, however it was not clear whether this was spinal flexion which is common during the gate start action or change in angle of trunk segment. The rider with the least amount of knee flexion (value not reported) and most trunk flexion produced the highest vertical bike velocity. No statistical comparisons were performed between the riders and the smallest worthwhile difference in the kinematics is unclear. As data from only one trial per rider is reported, the magnitude of between-trial variability is also unknown. Angular results in this study were reported to two decimal places, however validity studies of 2D marker systems suggest that this methodology may not be sensitive to this level (Maykut et al. 2015). This study provides some preliminary evidence that a larger range of movement in the trunk and smaller range of movement at the knee may produce result in a faster gate start. While this study provides some very general parameters around gate start kinematics, in the absence of a more robust comparison to performance and no validity or reliability data, it is difficult to take meaningful outcomes from this work to apply in practice.

Kalichová et al. (2013) studied BMX gate start kinematics of two riders. Five trials were completed by one elite male and one elite female on a gate with a ramp of unreported gradient. Only the fastest trial for each rider was analysed. Two 100 FPS cameras were used to record the motion and a 3D model was constructed based on markers at the wrist, shoulder, hips, knees, ankle and elbows on each side of the body (12 markers in total).

The gate start action was divided into five phases for biomechanical analysis as shown in Table 2-4. Movement descriptors including instantaneous velocities and joint angles were reported at the beginning and end of each phase for the shoulder, hip and knee. From the angles reported, the range of motion of the shoulders varied from 37° to 65°; hips: 30° to 66°; and knees: 63° to 78°. The study results show a clear asymmetry in the shoulders and elbow, however as only one trial was reported the generalisability of these results is not clear.

Table 2-4 Kalichova et al (2013) divided the gate start into these five phases.

Phase	Characteristic
1. Reaction time	Assume set position
2. Preparation movement	All movement before initiation of first pedal stroke
3. First pedal stroke	Starts at initiation of first pedal stroke and finishes when the cranks are parallel to the direction of gravity i.e. vertical
4. Dead point pedal passage	Time between first and second pedal stroke
5. Second pedal stroke	From point where pedal begins to move forward to end of second pedal (i.e. where crank is vertical again)

Further research in the area of upper body symmetry may be warranted. The reported knee range of motion is significantly different to the 17° and 18° degrees reported for the two riders by Giankellis et al. (2011), which may be due to different analysis protocols.

Kalichová et al. (2013) refers to the 'ideal technique' and the potential to use kinematic analysis in a coaching environment to provide quantitative feedback with the aim of improving performance. Kinematic parameters that constitute an 'ideal technique' are not quantified and objective information for the optimal gate start technique is not given in Kalichová et al. (2013) or any other known studies.

It was acknowledged by both assessors using the Quality Assessment Tool for Observational and Cross-Sectional Studies that Giankellis et al. (2011) and Kalichová et al. (2013) are better described as case studies rather than true observational studies because of the limited number of participants. There was limited detail in terms of the participants and data analysis procedures. These studies represent valuable preliminary investigations but were insufficiently powered in terms of participant and trial number to be able to provide a detailed kinematic description of the BMX gate start or its relation to performance. If more than one trial per rider had been analysed, then consistency of movement and associations between movement characteristics and performance could have been investigated. The limitations of Giankellis et al. (2011) and Kalichová et al. (2013) in regards to the number of participant and trials analysed make it difficult to draw specific outcomes that can be applied to enhance the training of BMX riders. A consistent finding from both studies was that the rider able to generate the greatest peak velocity reached the target destination first.

There are many factors that may possibly influence BMX gate start kinematics. Parameters such as rider anthropometry may be important in this context as the BMX bike dimensions do not vary greatly between bikes (top tube lengths vary by ~5 cm), so riders of varying sizes need to self-organise around the bike. The influence of gender, age, strength or experience on BMX rider kinematics also remains unknown in the scientific literature. Similar investigations in other human movements such as walking gait have used statistical tools such as regression, principle component analysis and hierarchical modelling to identify kinematic parameters that affect performance (Chow and Knudson 2011; Knudson 2009). These processes may be used in BMX studies to help to identify critical kinematics parameters worthy of further investigation. An improved understanding of these parameters would be useful in BMX coaching as it would aid in providing a more targeted focus in training and may improve the validity of performance feedback. More rigorous study into the kinematics of the BMX gate start action may provide insight into movement characteristics that optimise performance.

2.1.6.2 Importance of the Gate Start in BMX SX Racing

Riders and coaches alike agree that the start of the BMX race is critical to overall race performance. Trailing riders are more likely to make contact with other riders which can result in race-ending collisions (Mateo-March et al. 2014; Mateo et al. 2011; Zabala et al. 2009). Rylands and Roberts (2014) investigated placings at four time splits within four different 2012 World Cup events (Canada, Holland, Norway and USA). The first time split was typically at a point on the ramp and the last was at the finish line. Riders who placed 1st, 2nd and 3rd at the first split were more likely to achieve a top 3 ranking at the end of the race (Kendall's τ-b bivariate correlation ($\tau = 0.586$, $p < 0.01$). Race finish placing is important even in the preliminary qualifying heats (Motos) of competitions. Whilst the top four qualifiers progress to the next round (depending on the number of starters), the order in which they finish and lap time can impact lane selection privileges. Thus, much of the track based training as well as strength and conditioning training is focussed on improving the gate start action (Cowell 2011; Cowell et al. 2012a; Cowell et al. 2012b).

2.1.6.3 Power studies in BMX

The gate start action is a fast, forceful movement. Therefore, studies examining the relationship between muscular power development and gate start performance may provide insight into critical factors that influence gate start performance. Bertucci and Hourde (2011) have shown a strong correlation ($r > 0.70$) between performance in the first straight and other measures of performance such as peak power output generated during stationary cycling on an ergometer, squat jump and counter movement jump performance. Strength and conditioning coaches may benefit from greater quantitative data on the muscle activation and/or pedal forces produced during the BMX gate start to better match specific strength and conditioning exercises to this activity.

Recognising that the SX race start is an explosive action, Debraux and Bertucci (2011) aimed to define factors determining sprint performance. This showed the importance of understanding the relationship between power, cadence and gearing; however, studies to date have been limited by the availability of suitable valid and reliable power meters. Power has been measured using different power meters on a BMX, but the results may be limited by low sample rates. The SRM Powermeter (Schoberer Rad Messtechnik, Germany) and PowerTap (PowerTap, USA) were developed for road racing conditions where a low sample rate is used over extended periods (hours). The G-Cog (Rennen Design Group, USA) was the first power meter marketed specifically for use on a BMX and provides data sampling at 250 Hz. Bertucci and colleagues tested the validity and reliability of the G-Cog power meter and found that the results did not correlate with those obtained from the SRM (Bertucci et al. 2013). A response to this research was written by the manufacturers of the G-Cog suggesting that the use of a 2Hz signal (as per the SRM) to validate the 250 Hz signal (as per the G-Cog) is not reasonable (Costa 2013).

A power – cadence profile highlighted the importance of a smooth pedalling technique in order to optimise power (Chiementin et al. 2012). A power:cadence profile for 7 elite BMX riders sprinting on a flat 80 m track was created using a PowerTap powermeter (CycleOps, Madisson, WI, USA) with an undisclosed sample rate (Debraux and Bertucci 2011). This study suggested that the optimal cadence for peak power was ~ 120 rpm. This is consistent in other studies that measured optimal cadence for peak power with sprint cyclists using 6 s cycle ergometer trials (128 ± 7 rpm) and 65 m track trials (129 ± 9 rpm) for sprint cyclists (Gardner et al. 2007). Likewise, Martin et al. (2000) reported average values of 124 ± 8 rpm in a large sample of subjects (*n* = 86; 12-40 y). Rylands et al. (2013) discussed the impact of gearing as it relates to velocity generation and power generation in sprint events. During a 50 m maximal sprint test, BMX riders produced average (±SD) peak powers of 1030 W for 1 female and 1539 ± 148 W for 5 males. BMX riders typically generated more power in the sprint test than on the BMX track (the same bike setups were used for both tests). An important observation was that once BMX riders reached top speed they relied upon cadence to maintain bike velocity, highlighting the impact of gearing selection. Gearing choice is often optimised for gate start performance and the cadence quickly exceeds that which is optimal for power production (Rylands and Roberts 2014; Rylands et al. 2013). The impact of gearing, the fact that its selection is aimed at optimising start performance and that it remains unchanged throughout the race (generally single speed), suggests that factors that affect the gain ratio (gearing, crank length, exact tire circumference) should be reported in rider kinematic studies as they will certainly impact on the power cadence relationship.

Mateo, Blasco-Lafarga and Zabala (2011) showed that peak power did not occur during the first movements of the gate start action, but within the first 2 s of the start. In this study, riders performed a peak power output test on a stationary ergometer first which was compared to peak power output measure during the gate start. Riders then completed full-laps under three different conditions (no pedalling, gate start only pedalling, free pedalling) all on three tracks of varying technical difficulty. Power and average velocity were both measured using a PowerTap SL 2.4 powermeter (CycleOps, Madisson, WI, USA). The initial part of the race was described as strongly influenced by determinants of acceleration including slope of the ramp, and power generation. Peak power occurred in this phase, but not necessarily on the ramp, for all three tracks, with the average time to peak power being 1.42 ± 0.02 s, a point typically on the upward incline of the first jump, with a coefficient of variation of 2.5% across all results. This emphasises the importance of using a SX ramp that complies with UCI standards to specifically inform SX coaching, training and testing methodology. Limitations in power measuring technology must be considered when measuring time to peak power and other metrics such as peak torque. These are likely to be heavily influenced by the time it takes for the power meter to begin recording from a standing start as well as the sampling frequency and placement of the read switches on the power meter.

Cowell et al. (2012a) used the results of such studies to advocate power training for BMX riders. The importance of matching the component movements of the gate start action to gym based activities such as a dead lift is highlighted. Analysis of range of motion in all planes during the gate start action could be used to design gym based power development with greater specificity.

2.1.6.4 Skill Acquisition

Zabala, Sanchez-Munoz and Mateo (2009) looked at the importance of providing augmented feedback during a gate start training session for 6 elite riders. Augmented feedback was divided into knowledge of performance and knowledge of results. Knowledge of results is feedback relating to the outcome of the task, rather than technical aspects that may have contributed to task outcome. In this instance knowledge of results was the start - 4.5 m timing split. Knowledge of performance was given in the form of information about how the task was performed, such as the angle of the head, speed of the second crank and maximum angle of the torso. Video feedback was also used to relay information about performance to the rider. The impact of the intervention was measured immediately, 2 days and then 2 weeks post intervention. All participants received the intervention. The results clearly showed a significant reduction in time to 4.5 m after two feedback sessions for each of the individuals as well as the group mean results (average time 1.27 ± 0.05 s reduced to 1.04 ± 0.04 s). This learning effect was maintained when retested two weeks later. A limitation of this study was that it did not include a control condition involving only task-intrinsic feedback or compare different forms of augmented feedback. It is therefore unclear whether the augmented feedback was more effective than task intrinsic feedback, and if so, what form of augmented feedback would provide the greatest benefit. This study suggests that quantitative knowledge of performance including the use of kinematic parameters, may improve gate start performance outcome i.e. reduction in time split.

2.1.7 Conclusions

In conclusion, there is little published research in the area of BMX rider kinematics. Existing research in this area is exploratory only and uses small sample sizes and non-SX regulation gates. As yet there are no well controlled studies that describe the kinematic movement characteristics that optimise gate start performance. Research has demonstrated the importance of ecologically valid and reliable quantitative kinematics data that can be used to augment feedback for performance improvement (Zabala et al. 2009). Future research into valid methods of measuring rider kinematics and kinetics during the SX gate start would open pathways into investigation in these areas. Clear association between kinematic characteristics and gate start performance would be useful for coaches. It is expected that the strength of these relationships may depend upon a range of factors such as rider anthropometry and gearing, particularly in BMX because of the bike dimensions. In order to create ecologically valid information, it is important to collect data in the environment in which the results are to be applied. The BMX gate start is a more dynamic movement than those observed in other cycling disciplines and is unlikely to be effectively replicated on a stationary ergometer. If field based testing is used as an alternative, and the aim is to collect data that are meaningful to the SX gate start, the research data should to be collected on a UCI regulation 8 m gate. The literature in this area is expected to increase with the continued growth of BMX SX as a participation and spectator sport, with an increasing presence in the mainstream sporting world.

2.1.8 Addendum

Since the publication of this article only one more significant article has been published [16]. This was by a team that used a 20 camera Vicon 3D motion capture system (100 Hz) on a SX ramp that was built separate to a SX track for gate start training. This ramp lead onto a flat straight rather than into a jump as per a normal track. Twelve elite athletes each performed five trials using bikes fitted with a power meter (Shimano DXR with SRM spider, SRM, Jülich Germany, 100 Hz sample rate) to simultaneously record power profiles. Data from nine athletes were used for the kinematic analysis. Timing splits were taken at the base of the ramp and five m after the ramp on the flat. Performance was measured by a) time to the base of the ramp, and b) instantaneous velocity at the base of the ramp. Peak power, max cadence, cadence at peak power, mean starting velocity, mean starting acceleration and mean starting power were calculated using a distance of 18.68 m (the distance travelled from the start position to the base of the ramp) divided by the time split at the base of the ramp. Pearson's correlations found significant relationship between velocity at gate drop and power at gate drop ($r = 0.91$, $p < 0.01$). Participants were divided into *faster* ($n = 6$) and *slower* ($n = 6$) groups based on the velocity at gate drop. T-tests found significant differences between the two groups in terms of power and torque. The *faster* athletes were then found to extend more at the knee and hip than the *slower* athletes through the first four cranks and began the pedalling action before the *slower* athletes. The key finding was that the *faster* athletes developed speed earlier and used a larger range of motion in the hip and knee. The primary strengths of this study were the use of the 3D motion capture system, a greater number of participants and trials per athlete recorded and the greater number of relevant kinematic and kinetic outcomes presented than previous studies. The main limitation of this study was the relative lack of ecological validity due to the non-standard clothing and non-standard ramp used. The results of this study provided a sound base of data comparison for the studies presented in this thesis.

2.2 Discussion of research in other race cycling disciplines

In order to find additional literature to inform the analysis of the BMX gate start action, a brief review of literature in other cycling disciplines was undertaken. The cycling discipline with the most published research was found to be mountain biking. Similar to the research in BMX, little biomechanics specific research was found. This lack of research may be due to the relatively recent emergence of mountain biking as a high-performance sport and the logistical difficulty of performing research studies in the field environment. The paucity of published research in the biomechanics of performance in other forms of competitive cycling may also be due to embargoes on publication for competitive reasons. This occurs when such research findings are perceived to give a competitive advantage. In these cases, studies may only be released for publication once a significant event such as an Olympic games has occurred.

The cycling literature suggests that research studies conducted in the field rather than in a controlled laboratory are important as pedalling biomechanics can be significantly different when performed on ergometers in a laboratory versus when performed in field based conditions [51-53]. These differences in laboratory versus field based results suggest that laboratory based studies may lack ecological validity.

There would appear to be varying physiological and biomechanical demands between different disciplines of cycling, which would indicate the need for different analyses specific to each modality [54]. While there is research on muscle activation and kinematics from disciplines such as sprint cycling, these findings may not necessarily be directly applicable to BMX [55]. A key reason for this may be the different bikes and body positions used in BMX where the athlete remains standing throughout the race. An understanding of whole body movement patterns in BMX is particularly relevant because of the transfer of power through the torso to manipulate the bike over the gate and through the upper body dominant pumping action seen in the rhythm section of the track. As such, studies investigating movement patterns in other forms of cycling may not be directly comparable but may be used to inform the design of data collection for biomechanical and motor control research in BMX studies and this thesis in particular.

2.3 Review of literature relating to project methodology

2.3.1 Motion capture in biomechanics

Motion capture, digitisation and analysis are common practice in biomechanics and motor control studies. Where movement is predominantly in the sagittal plane (such as in BMX racing), it is common practice to use 2D analysis with research in cycling disciplines, with research suggesting that there is little additional advantage in using more expensive and complex 3D systems [56, 57]. Bini and Carpes [10] state that cycling movements in the coronal and transverse planes are small and of less interest as they contribute less mechanically to the application of force to the pedal than the sagittal plane movement. Fonda et al [57] showed that the sagittal knee angle measured with 2D motion capture compared favourably to that measured in 3D and with a goniometer measurement for a cyclist on an ergometer. Infrared cameras (3D), high speed (2D) cameras and an electrogoniometer were used to measure the knee angle during pedalling. The electrogoniometer and 2D motion capture underestimated the knee angle as measured with the 3D system ($P = 0.00$; η (2) = 0.73) by 2.2° which was considered acceptable considering the range of motion at the knee during pedalling which was ~ 140° [57, 58].

2.3.2 Definition of determinant phases

Motor control uses the division of actions into subcomponents, often referred to as phases, to analyse movement control and performance [59]. Even simple movements, such as finger pointing, can be divided into subcomponents. This allows for an understanding of the movement in terms of muscle activation patterns, spatial and temporal movement and sequencing. Dividing a movement into phases helps with the development of part practice of a complex movement, whereby a subsection of the movement is initially rehearsed in isolation [59]. Analysis of phases of movement allows identification of weaknesses and strengths as well as facilitating the identification of what aspects of the movement have the greatest impact on performance outcome.

In dividing a movement into phases, it is important that the phases can be clearly identified and occur consistently between trials and individuals, with relative time, force and sequence remaining consistent [49]. One of the earliest studies in this area was described in Soechting et al [60] in 1981. The aim of the study was to identify the invariant phase features of a simple pointing movement, with the idea being that such invariances would reflect the organisation of the movement by the central processing in the brain. This reflects the concept of the General Motor Program (GMP), which describes movement as centrally organised in the brain. The pointing study in Soechting et al [60] identified two phases, an acceleratory phase where the ratio of elbow angular velocity to shoulder angular velocity remained invariant with respect to target, and a deceleratory phase [60]. A similar study that examined walking and running gait showed that when speed increased the absolute time per phase decreased, however the relative time per phase stayed the same within each gait activity [61]. The phases were identified as different between running gait and walking gait thereby defining running as a different locomotive task.

The Schmidt Schema Theory (SST) describes how the GMP controls coordinated movement [59]. For the definition of a distinct movement, the SST uses various parameters to define the bounds of the movement. The first parameters describe the initial body position of the movement. In the BMX gate start, the initial parameters describe the starting set position. The second parameters for movement definition are scalable parameters such as speed and force. For example, to walk at 0.5 m.s^{-1}, the angular velocity required at the knee joint and hip joint is less than required to walk at 1.0 m.s^{-1}, however the relationship between the angular velocities of the two joints remain similar [61]. Thirdly, the sensory response to the movement is consistent between trials, i.e. it ‘feels’ similar each time. Finally, the outcome of the movement is similar, meaning if the aim of the movement is to throw a ball, the outcome is that the ball is thrown [49]. One of the most important aspects of the SST is that each movement is characterised by invariant relative-time sub-movements. Thus, a movement can be described as either a distinct series (as a gate start), or cyclic series (as in gait) of sub-movements, or phases, that each represent an invariant percentage of the entire movement.

Phases can be used to analyse an athlete's movement performance. For example, research that divided the swim start into *block*, *flight* and *entry* phases showed when and where the impact of different swim start set positions occurred [62]. A study in swimming examined the effect of using the conventional track set position compared to a one handed track set position in elite age group swimmers on the *block* time and *flight* time [63]. Six of the 12 national level athletes learnt the new one handed technique, then all 12 participated in 4 week intervention comprising 12 ± 3 thirty minute training sessions. Temporal and kinematic data were extracted from video footage and force data were collected with a portable force plate and load cell handrail mounted to a swim starting block. Each athlete performed three trials of each technique. The study found a significant difference between the intervention and control groups in time to 10 m, total time, peak vertical force, flight distance and horizontal velocity at take off ($p < .05$), with the conventional start giving better results in all areas. The study also demonstrated that a set position intervention can be used to improve peak horizontal force and velocity at take off, *block* phase time and *flight* phase time. Such a research approach in which phases are identified, athletes are profiled across phases, interventions are developed based on the athlete profile, and the intervention effects are subsequently analysed, can be applied to other sports including BMX.

The concept of SST has been applied to pedagogy in order to facilitate skill acquisition. For example, the subcomponents of a whole action which can be learnt and practiced in isolation. As learning progresses subcomponents can be pieced together to form the whole action [64]. For the application of the BMX gate start, this has two implications, one being that if phases can be identified they can then be trained in isolation, and the second being that if there are phases that are common to other actions then this learning will transfer to these other actions [59]. A BMX racing example is the use of the upper limb flexion and extension that characterises aspects of both the gate start and the pumping action used in the rhythm section of the track.

Breaking a movement into components can also make it easier for a learner to understand. This is commonly done with a variety of sporting actions including the golf swing. For example, websites outline distinct phases for beginners, and how to improve each phase [65]. As an example, the difference in the movement characteristics in these phases between professional (*n* = 15) and amateur (*n* = 15) golf players was investigated by Sim et al [66] with the use of 3D motion capture of the pelvis and thorax. It was found that there was a significant difference in the backswing flexion and extension through the spine, and in the coupling angles, however there was no difference in the overall coordination pattern for rotation. The differences in each phase can be used by coaches to help amateur golfers improve their swing to more closely resemble that of the professional golfers. Thus, it can be seen that by breaking a movement into phases a greater understanding of the movement can be obtained in terms of the difference between higher and lower level athletes and the likely implications this may have on performance.

2.3.3 Study of movement variation

Movement variation is a natural phenomenon observed with any repeated action. A skilled practitioner is assumed to apply optimal movement variation in order to accommodate injury, efficiency, fatigue, etc., and to allow for changes in the environment, task or organism constraints. In contrast, less skilled individuals may be less able to vary movement when faced with these changing constraints. These differences in the ability of skilled versus less skilled individuals to vary movement may be one of the defining differences that distinguish skilled and less skilled performance.

A commonly used quantifier of movement variability is the coefficient of variation (*CV*) which is defined as the standard deviation/mean and is expressed as a percentage (*SD*/*mean* x 100) [67-69]. The *CV* can be used for singular measures such as peak angle, or angular velocity at a pre-defined point of time. When variability of a continuous movement needs to be measured, a bandwidth is often used [70]. Taylor, Landeo and Coogan [71] examined intra-individual movement variation of elite water polo players during a water polo shot. The water polo shot is a key determinant of performance as it is the most common approach for goals to be scored. Seven participants were used, each completing 10 trials where accuracy was recorded as hit/miss in a non-competitive environment. Movement was measured using six opto-electric cameras at 250Hz from which a 3D model was generated. For each throw, elbow and wrist velocity were calculated, and a discrete outcome result of hit/miss recorded. Group results were reported as a standard deviation of the measurement at ball release. For each participant, variation was reported for each accuracy condition (hit/miss) by *CV*. Elbow and wrist angle and wrist linear velocity *CV* were graphed against time, showing a change in variation throughout the movement for all variables. The greatest variation in elbow angle (9.4 - 16.4%) occurred at the end of the movement and was greatest when the target was missed, but least when it was hit. Wrist angle varied most at the start of the movement (6.3 - 7.1%) and the miss trials had the highest variability. The greatest variability measured was in wrist velocity, with *CV* peaking at 29.2% for miss trials at 40% of the movement time. This suggests that in elite athletes, the magnitude of movement variability for the joints undergoing the most motion may change throughout the range of motion and be less for a hit (successful performance outcome) than a miss (failed performance outcome).

Witte et al [72] examined the mae-geri karate kick using five highly ranked participants. Five different angles were measured representing the knee, hip, torso angle, pelvis rotation and pelvic tilt using a 3D motion capture system. Variation in angle against time was calculated to give within subject angle variation at the five joints. This approach was able to provide some insight into how movement variation changed as a function of range of motion for each joint and which joint exhibited the least variation across all participants. These analyses could also be used to rank the participants in order of movement consistency and perhaps provide some indication of maturation of movement [55, 73, 74]. It may be possible to apply this methodology to the study of BMX gate start skill acquisition.

2.3.4 Markerless motion capture

Motion capture is the most commonly used method for collecting kinematic data. It is typically done by placing markers such as retro reflective spheres on the subject and then digitising the marker movement, thereby translating the information into a 2D or 3D coordinate system. While widely used in research, it is recognised that there are limitations to this mode of motion capture, especially for high-speed activities in the field [18, 59]. The first of these limitations is soft tissue artefact: that is, movement of the marker relative to the bone structure beneath the skin. This has been shown to be dependent on the subject, task and kinematic variable being measured and can result in statistically significant errors of measurement [59]. If the markers are placed on clothing, even greater soft tissue artefact will likely occur as the clothing moves relative to the skin [75]. In field testing environments where clothing must be worn, the clothing should be close fitting such as compression wear garments to minimise soft tissue artefact. BMX athletes wear loose fitting garments over protective clothing during training and competition making the use of such markers difficult. Changing the clothing worn by the athletes to accommodate a marker based system may compromise athlete safety by removing bulky protective items such as knee pads and alter the ‘feel’ of the movement, and thereby result in a change of action.

The second limitation is that joint centre of structures such as the knee move with the change in joint angle. This change means that the marker’s validity changes during movement [76]. An analysis of six different methods of estimating shoulder joint centre showed that different joint centre estimation methods produced different angular measurements [77]. Campbell et al [77] compared the use of a new regression model and six established methods to estimate glenohumeral joint location and compared the result with the location as identified with magnetic resonance imaging. The new regression method tested in Campbell et al [77] was closer than any of the six other established methods with a location error of 13 ± 2 mm, and significantly lower inter-tester reliability error, 6 ± 4 mm ($p < 0.01$). Because much of the movement in a BMX gate start occurs at the hip, knee and shoulder, all of which are internal joints with axis of movement that vary according to the position of the relevant limbs, the use of markers may lead to misleading joint centre information and thereby systematic error in joint angle calculation. Virtual markers imposed on an image of a BMX athlete on the bike enables the estimated joint centre to be moved between frames in accordance with the body position which accommodates this variation in joint centre with movement.

An alternative approach to marker-based motion capture is markerless motion capture. In markerless motion capture, body segments are visually estimated, and the joint centres are placed at the intersection of the linear body segments. In 3D analysis, markers are placed on landmarks that are used to generate body segments that then form the basis for estimated joint centres which cannot be physically marked as they are internal to the body, such as the hip joint centre [78, 79]. The estimation process and associated potential for error in both marker and markerless methods need to be taken into account during analysis when looking for significant differences in movement patterns using kinematic analysis.

With the improvement in video camera technology, markerless motion capture in situ has become more common in field based sports research as is shown in Table 2-5 [80-85]. This allows for the activity to be performed in a realistic manner where the task constraints (such as using a real BMX bike on an Olympic SX gate start), and environmental constraints (such as weather, peer pressure and start gate equipment) can be very similar to that seen in the real competition. As such, markerless motion capture can improve the ecological validity of sports science research which is warranted as studies show that laboratory tests results do not always correlate to on-field performance [51, 54, 86].

Multiple cameras with high speed frame rate (≥ 60 FPS) and high definition picture quality of at least 640 x 480 pixels are recommended for markerless motion capture in the literature and enable comparable results to 3D systems [10, 87]. Schmitz et al [88, 89] compared a markerless motion capture system (Microsoft Kinnect) to a 3D retro reflective motion capture system. In the static study where a jig was used as a subject, the angle measurements from both systems agreed within < 0.5° in the sagittal and frontal planes with a coefficient of reliability of < 0.5° [89]. A second study within Schmitz et al [88, 89] used a person doing a squat and measured hip and knee angles. Movement patterns reported by both systems were similar and peak joint angles correlated between systems with r values $0.5 > r > 0.9$ for angle measurements in six degrees of freedom [88, 89]. Using markerless motion capture in 2D, Bowerman [90] reported an intra-tester reliability of ICC ≥ 0.95 for a vertical drop jump and in a validity study comparing 2D to 3D, an ICC = 0.92 in the measurement of extremity alignment in nine elite adolescent ballet dancers. The difference between the 2D and 3D measures was 1 - 2° for knee and pelvic angle measurement.

As only one tester was used for the proposed PhD project, there was no potential for inter-tester variation. However, intra-tester measurement variation is recognised as a potential source of error in the field of motion capture. For small data samples, a re-test of 40% trials has been used to establish reliability of the markerless method [91]. For larger sample sizes a re-test of 10% is common [18]. An intra-tester correlation coefficient of > 0.8 for intra-tester reliability has been deemed acceptable [90, 92], which was used as a reference for this PhD program of research.

Table 2-5. Summary of research using Kinovea to measure kinematics from Proquest.

Author Date	**Activity**	**Question**	**Outcomes**	**Marker system**	**Markerless system**	**n**	**Findings**
Balsalobre-Fernández et al 2014 [84]	Counter movement jump	Compare Kinovea to infared platform	• Flight times	Infrared platform	Kinovea / Casio Exilim FH-25 camera @ 240 FPS	25	Perfect correlation between systems (ICC = 1)
Bowerman et al 2014 [90]	Fondu (ballet)	Relationship between kinematic patterns related to overuse and physical maturation	• Pelvic angle • JA (knee) • Foot length	N/A	Kinovea / Panasonic camera @ 240 FPS	46	It is possible that there is a relationship between risk of overuse injury to physical maturation.
Abd El-Raheem et al 2015 [93]	Wrist movement	Intra and inter tester variability using Kinovea to measure wrist ROM	• ROM of wrist	Retro reflective markers	Kinovea / CANON A-810 camera @ 25 FPS	100	Kinovea intra-rater reliability ICC > 0.926 Kinovea inter-rater reliability ICC > 0.877
Potop et al 2015 [94]	Double back somersault on floor (gymnastics)	Describe kinematics of the double back somersault on floor	• Time splits • Body segment angles • Distance between body segments • Anthropometry	N/A	Kinovea / camera @ 30 FPS	13	Relationship between kinematics and anthropometry
Ayad et al 2015 [95]	Forward reach (infant)	Motor development of infants - interventions study using a family based program.	• time of movement • peak velocity	Markers	Kinovea / Sony digital camera (FPS not given)	124	Motor development can be influenced by family based intervention programs

FPS frames per second, ICC interclass correlation, JA joint angle, N/A not applicable, ROM range of movement

2.3.5 The use of Kinovea

There are many different motion analysis software packages available. The best package depends on the user's experience and the intended application. Kinovea is an open source software package and available at www.kinovea.org. For the studies in this project, Kinovea was selected as it was commonly used by CA, it was free, capable of doing all the analysis required and exporting data in a format easily accessed by Matlab (The Mathworks, USA).

Kinovea has been used in biomechanical research for applications ranging from sprinting to cliff jumping [54, 82-85, 96]. Table 2-5 summarises research done using Kinovea. All scholarly literature returned from a search in Proquest on "Kinovea" AND "biomechanics" in English that used Kinovea to measure kinematics were reported. Only some of these studies examined the validity or reliability of Kinovea. The first article by Balsalobre-Fernández et al. [84] showed a strong correlation (ICC =1) between the time splits measured from Kinovea and those returned by an infrared platform when vertical jumping. Intra-tester reliability was demonstrated to be high (ICC > 0.9) by Abd El Raheem et al [93] during a range of wrist movements. This high reliability measure supported the use of Kinovea and was a guideline for expected intra-tester results. The analysis method used in a study aimed to quantify kinematic parameters of the double back somersault as seen in a gymnastic floor routine [94] was similar to that used in Study 5, with video footage of the sagittal plane analysed in Kinovea and kinematics of interest exported for numerical and statistical analyses.

While markers such as coloured stickers or retroreflective markers are often used to identify joint centres or surface anatomy, this is not a requirement for the use of Kinovea. Kinovea enables the application of virtual markers to the body by laying them on the image digitally within the Kinovea application. Kinovea recognises the coloured pixel clustering to which the marker is applied and attempts to follow this particular cluster from frame to frame to trace the movement of the virtual marker automatically. In situations where there is clothing movement relative to the body, changing light or interference with the line of view this automatic tracking process is difficult as the desired marker location changes colour and is no longer recognised or is misplaced by the auto-tracking algorithm in Kinovea. This can be remedied however by re-placing the marker on the desired location. The advantage for such a process in a project such as this one with BMX is that it negates the need for markers on baggy clothing and enables the tracking of joint centres despite changes in light, etc as required for data collection in situ on the ramp.

As demonstrated by this literature, markerless motion capture and data analysis in Kinovea is an accepted method of kinematic measurement within biomechanics. This is particularly the case in sports biomechanics, where environmental factors make the use of marker and multi camera systems logistically difficult and where marker based systems may reduce the ecological validity and/or safety of the athletes.

2.3.6 Simple reaction time

Simple reaction time (SRT) was first defined in 1868 by Dr F.C. Donders [97]. Donders is recognised as the first to study mental chronometry, which is the use of response time to map the timing and sequencing of mental operations following a perceptual stimulus [59, 98]. SRT involves a singular response to a singular stimulus, such as pressing a specific button when a specific light is turned on. The actor makes no choice regarding the action, and as such SRT is often considered an index of neural processing speed [99]. SRT is the recognition of stimulus and motor planning or action preparation before movement is initiated, and the time it takes once muscles are activated to make the required response [100].

In Figure 2-3, the actor is asked to jump when the red light flashes on. The stimulus is the red light. First of all, the actor recognises the red light as the ‘go’ stimulus; this is referred to as *stimulus recognition*. The central nervous system then works out what the body needs to do in order to jump. This is the *premotor planning*. The *motor response* phase involves the activation of the muscle to perform the motor skill (in this case ‘jump’), which is the final *stimulus response*.

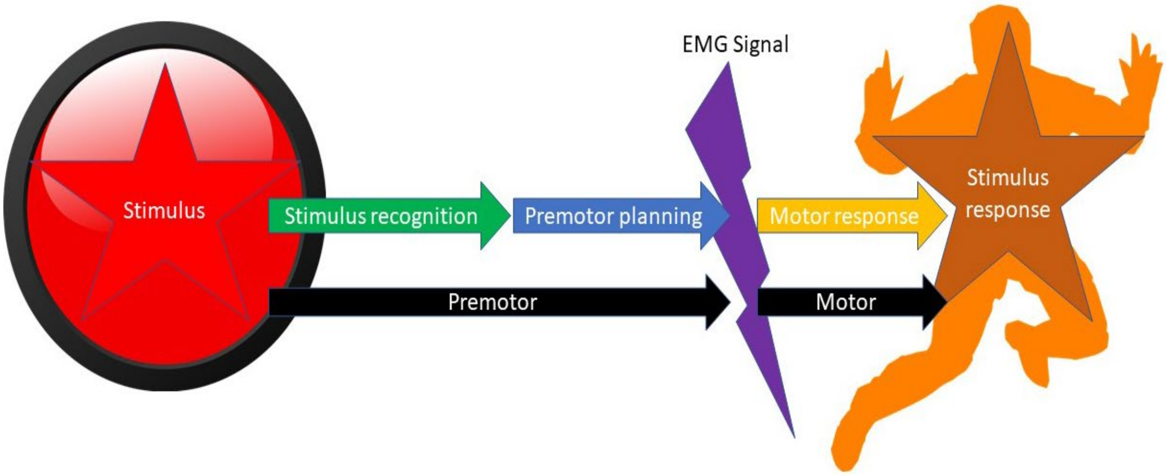

Figure 2-3 The components of SRT

Stimulus recognition and *premotor planning* have been described as two quite separate and distinct activities, one afferent, and one efferent [101]. Each of the two components, *signal recognition* and *motor planning*, may be differently affected by factors such as arousal, practice, and distraction. Factors such as stimulus volume, duration, predictability of intensity, and variation in tone have all been found to impact *stimulus recognition* [59, 102, 103]. Factors such as movement complexity, movement familiarity and sensory integration impact *premotor planning* [59, 104]. These two phases (*stimulus recognition* and *premotor planning*) can be added together (referred to as the *premotor time*) and are measured as the time from stimulus to muscle stimulation as measured with electromyography (EMG) [59, 100, 102, 103]. *Motor time* is the time between when the efferent motor nerve action potential is detected at the muscle the EMG and the stimulus response. Studies have shown that while the duration of *premotor time* is affected by modifiable variables such as arousal levels, the *motor time* is consistently variable (i.e. varies the same amount each set of trials) irrespective of change of arousal, practice, duration etc. [59, 100, 102, 103, 105]. On this basis, any changes in SRT due to an intervention can be assumed to occur within the *premotor time*.

Race time is the time between the start signal and the athlete reaching the end of the race. The first component of this can be considered SRT. The smaller the total race time, the more significant the SRT is in terms of race outcome. In events such as BMX SX where the lanes are not delineated after the start and there is a competitive advantage in being ahead as soon as possible, the SRT may be an important factor in getting in front of other competitors in the first 2 s of the race on the start ramp. If the SRT is around 200 ms [105], this represents 10% of the ‘race within the race’ that occurs on the start ramp.

Choice reaction time (CRT) is an important component of reactive sports such as handball, martial arts and baseball [106]. CRT involves a decision about the required *motor response* based on the nature of the stimuli before the movement is initiated. CRT is significantly longer than SRT (for example, 384 ms compared to 220 ms as reported in Laming [107]), however SRT is a component of CRT, and *premotor planning* and *motor response* have been shown to be relatively invariant between SRT and CRT [108]. As such, there is potential for training-related improvements in SRT to transfer to CRT tasks, as long as the training improves *stimulus recognition* and *premotor planning*.

In sprint events such as BMX SX there are both auditory and visual start stimuli. The difference between SRT for auditory and visual stimuli has been well researched, with findings showing auditory SRT averaging 140 - 160 ms and visual SRT averaging 180 - 200 ms [109]. This difference in RT is partially because sound signal travels from the ear to the auditory processing section of the brain more quickly (8 - 10 ms) than the visual signal travels from the eye to the visual processing centre (20 - 40 ms) [110]. The speed of sound in air is 333 $m.s^{-1}$ whereas light in air travels at 299792458 $m.s^{-1}$ which is considerably faster, meaning that the light signal will get to the body more quickly than the sound signal. So, assuming that both auditory and visual signals occur instantaneously at the stimulus source, it can be assumed that they will not both reach the processing part of the brain at the same time. While the light signal may reach the body first, the auditory processing occurs more quickly so the response to the auditory signal may occur first.

Race timing systems link the device that produces the start signal (visual and/or auditory), the reaction measurement device and the clock through a black box as per Figure 2-4. This means that the ‘start’ of the reaction time reported on the clock occurs when the signal is given at the source, rather than when it reaches the body.

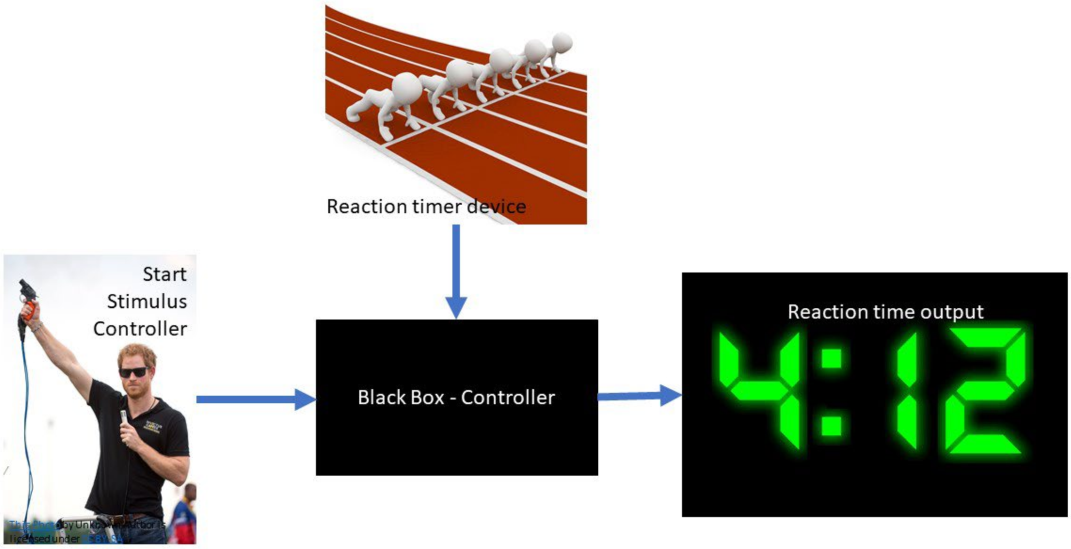

Figure 2-4 Black box controller for measuring reaction time

The horizontal force on the blocks is often used in track athletic events to measure the end of the reaction time because it is considered an indicator of the first ‘functional’ movement contributing to the first forward propulsive action [111]. Defining the first ‘functional’ movement in BMX SX is more difficult, partly because of the variety of techniques used even by WC athletes, and also because many athletes actually propel the bike backwards during their first propulsive action. This initial rearward movement is explained further in Study 5. There remains scope for additional discussion as to what constitutes the ‘stimulus response moment’ in a BMX gate start.

Mero et al [112] conducted a study that used electromyography (EMG) to measure RT components. Eight male sprinters performed three maximum effort starts on a force platform. Four participants had EMG electrodes fitted to the front leg, and four to the rear leg, where the front leg was the most forward leg in the set position. Conventional starting blocks were used. The ground force reactions (GRF) were recorded from the start signal and mapped to the EMG signal. The results from Mero et al [112] (Table 2-6) showed that an EMG response could be measured at 8 - 113 ms post stimulus which were well below the GRF based RTs.

Table 2-6 RTs from EMG data presented in Mero et al [112].

		Front leg **Ave ± SD (ms)**	**Rear leg** **Ave ± SD (ms)**
GRF RT		121 ± 114	119 ± 11
Pre Motor	Lateral Gastrocnemius	64 ± 45	101 ± 42
	Vastus lateralis	79 ± 36	90 ± 14
	Biceps femoris	97 ± 24	96 ± 2
	Rectus femoris	110 ± 19	99 ± 40
	Medial Gastrocnemius	113 ± 18	74 ± 16
Motor	Lateral Gastrocnemius	57 ± 50	18 ± 29
	Vastus lateralis	42 ± 49	29 ± 4
	Biceps femoris	24 ± 10	23 ± 3
	Rectus femoris	11 ± 19	20 ± 28
	Medial Gastrocnemius	8 ± 9	45 ± 9

The International Association of Athletics Federations (IAAF) considers a RT of less than 100 ms to be a false start in sprint races in athletic events [113]. In an athletic sprint start, the start RT is officially measured as the time from the start signal to the time at which the GRF exceeds 20 kg [114]. Therefore, the rate of force development is an important aspect in track and field sprint events. If a sprint athlete finishes the premotor reaction at 65 ms and develops the GRF quickly, reaching the threshold at < 100 ms, they will be disqualified. However, if their neighbour finishes the pre-motor reaction at 65 ms and develops GRF more slowly and does not reach the threshold until > 100 ms they will not be disqualified. This means that there may be two results for the same actual initial response time. As a result of this rule it is believed that athlete's RT has increased during formal competition due to fear of disqualification [115, 116].

Tonnessen et al [117] found a significant correlation between RT and 100 m running time (*r* = 0.292 for males and females *r* = 0.328) across 1,319 athletes competing in the IAAF world championships between 2003 and 2009. Further support for the importance of RT to race outcome can be seen in Delalija et al [114], where significantly faster RT were observed in short versus longer track sprint distances in 250 female athletes and 360 male athletes in the 2004 Olympic Games. Specifically, RTs were 184 ± 22 ms for female athletes and 164 ± 24 ms for male athletes for the 100 m race, and 281 ± 68 ms for females and 259 ± 51 ms for males for the 400 m race. Brosnan et al [113] also showed that male and female athletes significantly differ in their RT (male threshold 115 ms and female threshold 119 ms).

Various studies have investigated interventions to improve simple RT in sprint events with the intent to improve overall race performance. The most common intervention in the literature is pharmaceutical with caffeine being the drug of choice for many athletes [118-120]. Caffeine acts to increase muscle recruitment by aiding in the blockade of adenosine receptors in the brain [120]. It also promotes calcium release at the site of muscles thereby facilitating muscular contraction [119]. Santos et al [120] found that reaction time was significantly reduced after ingestion of 5 $mg.kg^{-1}$ of caffeine. Ten experienced (> seven years of training) taekwondo athletes were divided into a placebo and intervention group. The RT was measured based on a standard bandal tchagui kick, which is a simple one-legged kick normally rehearsed in training by all athletes. The athlete was instructed to perform the kick in response to a visual stimulus and RT was measured by a movement sensor attached to the heel of the athlete. The caffeinated group reacted more quickly (−11.9%, $p < 0.01$) than the control (placebo) group, although the overall kick time was not different between the groups. An important component of RT that caffeine may enhance is the ability to better focus on the stimulus. Durlac et al [118] demonstrated that 60 mg of caffeine reduced the effect of a distractor on RT in a key press test. Furthermore, caffeine was shown to have an effect within minutes [118]. Other stimulants such as amphetamine, ephedrine and cocaine can have similar effects but are not permitted in competition [121, 122].

There also appears to be some evidence that RT is a trainable quality. de Souza et al [123] demonstrated a learning effect in a sensory threshold detection training exercise for an auditory stimulus but not a visual stimulus. It has also been shown that athletes (collegiate level) have significantly faster RT at both a fine and gross motor level than non-athletes [109]. This suggests that there is something in the athletic training process that affectively ‘trains’ RT, or ‘selects’ individuals with naturally occurring fast RT.

The trainability of race start RT was also investigated by Papic et al [124]. Ten elite swimmers (Australian national and state level) were recruited, all of whom attended at least four aquatic sessions per week during a four-week training intervention with the aim of improving race start RT. RT was measured as the time from the ‘go’ stimulus (electric horn) until a change of GRF as measured by a bespoke device on the start blocks. The intervention group added a competition specific auditory stimulus to their normal swim start training program and performed an average of 60.6 ± 15.0 dives across the four weeks, while the control group did not change their usual swim start training and performed 44.2 ± 15.6 total dives across the four weeks (no significant difference between groups in number of dives completed). Prior to the intervention there was no significant difference in RT between the groups (control group RT = 140 ± 9 ms versus intervention group RT = 131 ± 14 ms). Following the four week training study, the intervention group demonstrated a decrease in RT by ~ 13 ms. This created a significant difference in the average RT at follow up (intervention group RT = 119 ± 11 ms, control group RT = 149 ± 16 ms). These results indicate that race start RT can be reduced with specific training. Interestingly, it was reported that there was no change in the total amount of time swimmers spent on the block (from the start signal to leaving the block to start the flight phase) in either group, and no evidence to suggest such an intervention makes a difference to race results. No known studies have been found investigating whether RT can be improved in any sprint cycling or BMX events.

2.4 Gaps in the literature and the relative position of this project

There are many questions regarding ways to improve BMX performance, especially with respect to how research in the fields of biomechanics and motor control may improve the BMX SX gate start. Table 2-7 provides a summary of some of these gaps in the literature and the relevant study within this thesis which seeks to address each gap.

Table 2-7 Gaps in published research in the area of the biomechanics of the BMX gate start action.

Themes not previously investigated	**Thesis study that investigated this theme**	**Thesis study from which this can be derived**
Common range of motion	5	
Common joint angular velocities		5
Common movement ‘shapes’	5	
‘Normal' movement patterns	1,2,5	
Hub trajectory 'shapes' and the consistency of this between/within athletes	5	
Kinematics that correlate to kink time	1,2,5	
Parameters of rear movement of the bike	5	
Parameters of vertical movement of hub trajectory	5	
Invariant phases	1	
Differences between WC/Elite	2	5
Differences between male/female	2	5
Gate start reaction time	1,2,3	
Validity and reliability of an ecologically sound method for kinematic analysis.	4	
Movement variability	5	
Appropriate off-track training		1,2,3,5

A descriptive biomechanics study seeks to identify and define key components of a skill by breaking the movement down into phases and describing the characteristics of each phase. The research presented in this thesis sought to determine possible relationships between movement characteristics and performance outcome. It will be the first known published study to identify the movement characteristics related to optimal kink time for the BMX SX gate start.

The literature review (reported in Section 2.1) demonstrated that very little peer-reviewed research has been published on BMX biomechanics, leaving many potential research areas requiring further investigation. On this basis, the program of research presented in this thesis reported on the kinematics of the BMX SX gate start action in situ through a series of five studies.

Study 1 (Chapter 4) divided the gate start action into distinct subcomponents, or phases. Study 1 was unique as it was the first known study to apply Schmidt's Schema Theory to the BMX gate start action and define phases that are temporally invariant between and within athletes. The defined phases could be applied by BMX coaches in the field on any track, and even on training ramps. Previous studies [60, 65] had based phase definition on movement characteristics, but also on factors that are determined by environment constraints rather than the performance of the action, such as passing the edge of the gate. Study 1 provides a robust new framework for performance analysis and monitoring athlete kinematics during the BMX gate start.

While it was well documented through race timing data that female race speeds are, in general, slower than male race speeds in BMX SX events, the source of those differences had not been investigated in known literature. Study 2 (Chapter 5) used the phases defined in Study 1 to explore possible causes of the difference in race times between genders. Similarly, potential differences between WC and Elite athletes was investigated, with these comparisons building on the preliminary work presented in Gross et al [16]. The within and between participant variability of phases were quantified and allowed further quantification of the difference between WC and Elite, and female and male athletes. Identifying movement characteristic variation may provide an understanding of what reflects a “normal” amount of variation as well as quantify the stability of the different movement characteristics across multiple trials within the same training session. Such information is important for two primary reasons. The first of these reasons relates to the concept of functional movement variability, where experienced performers may be able to modify some aspects of their coordination patterns in an adaptive fashion to account for changes in the encountered constraints across multiple trials. The second reason is that BMX coaches and sport scientists require an understanding of the magnitude of typical movement variability in order to be confident that any change reflects a true change to a movement pattern and is not just natural variation or measurement error.

While RT studies have been undertaken to investigate the efficacy of start reaction training [109, 124-126], no known published research has investigated the impact of this training on RT in a BMX SX gate start. Study 3 (Chapter 6) was a preliminary investigation into this field of performance improvement and added to the RT training literature presented in Papic et al [124] on the swimming start.

In Study 4 (Chapter 7), the repeatability and reliability of a new marker-less motion capture methodology was reported. The use of a novel method of motion capture was required due to the loose protective clothing worn by BMX athletes and the nature of the SX ramp which made the use of the gold standard 3D marker based motion capture in a field setting prohibitive.

Study 5 identified movement characteristics relevant to BMX kink time. This provided a robust description of the kinematics of the BMX SX gate start. The relationship between the measured kinematics to kink time was also investigated. This had been recognised as important but not rigorously investigated in known literature [127]. The results presented in Study 5 enable the comparison of an athlete’s technique to a benchmark. This may help coaches provide meaningful advice to athletes regarding kinematic variables such as trunk angle and may prove invaluable to BMX coaches and sports scientists by accelerating the rate of the athletes’ gate start skill acquisition.

The studies in this PhD research program assessed not only pure biomechanical kinematics as previously researched in other cycling disciplines by biomechanics researchers [10], but also parameters considered important through empirical analysis by highly experienced coaches and elite athletes. The outcomes have provided quantitative parameters that can be used by coaches to help athletes improve kink time. This addressed the gap described by Zabala, Sánches-Muñoz and Mateo [14] between sports science research and its application to improving BMX performance.

While the studies presented in the thesis flow together to make a cohesive research story, it is recognised that each contributes to the field of BMX biomechanics in its own right and may be read in isolation. Each study is therefore written as a stand-alone manuscript, resulting in some repetition of information throughout the thesis. This has been done for two reasons; firstly, because some studies have already been published and others are in preparation for submission, and secondly because it enables researchers and coaches to comprehend each study without having to read the whole thesis.

Chapter 3: Data collection Environment

3. Data collection environment

In keeping with the aim of the PhD project to examine 'real world' movement characteristics, all data for this project was collected at CA and BMXA gate training sessions to maximise ecological validity. CA and BMXA gate training sessions for SX racing were held at the Sleeman Park SX Track, Brisbane, Queensland, Australia. They were conducted under the supervision of the BMX HPU staff, including the head coach and sports physiologist.

Ecological validity was an important issue that was discussed at length in designing the data collection protocols for this thesis and led to the development of a markerless motion capture methodology that employed action cameras and Kinovea. The markerless method negated the need for changing the clothing worn by the athlete and did not interfere with the track or training program. Employing this methodology ensured minimal disruption to the athletes' action so that the data captured represented as unadulterated movement pattern as possible.

Each training session lasted for two - three hours. The first half hour was typically a track warm up period where the third and fourth straights were ridden including rolling accelerations (sub-maximal sprints) from the turns. The remainder of the training sessions were driven by each athlete's needs and included performing multiple maximum effort gate starts. Up to eight riders were included in a single gate drop. The UCI standard BMX SX gate procedure was used (as per Appendix 4). After descending the start ramp, the athletes would typically take the first one - two jumps and then taper off at the end of the first straight. This represented about a quarter (~ 100 m) of the complete track. The athletes then returned to the start. Rest periods between trials were self-selected and typically ranged from three to 15 minutes.

After each trial, timing data from the radio frequency identification (RFID) system was obtained. The RFID gave timing splits for the *start to kink* (i.e. kink time), *kink to ramp base* and *start to ramp base*. After some of these trials, the coach asked the athletes some questions and/or provided knowledge of performance feedback in the form of his visual observations as well as footage from hand held cameras. These questions from the coach helped the athletes to utilise their intrinsic feedback. This was typically in the form of the question, “How did that feel?”, followed by the presentation of the kink and ramp timing splits, and then video footage if this was available and warranted. The coach may then advise on areas of focus and/or technique changes where appropriate.

Athletes performing gate starts in these sessions were of varying performance levels from national level junior elite to world class HPU athletes. Between three and 20 athletes were present at any given training session. Some training sessions were not restricted to DA and HPU athletes only, however only DA and HPU athletes participated in the research program. All participants were informed of the nature and risks of each study before providing written informed consent using the forms presented in Appendices 5 and 6.

The video footage collection procedure was standardised and followed the proforma described in Appendix 7. A minimum of two hours was required to prepare and check all equipment. A research assistant stood on either side of the gate throughout the training session to monitor the battery and memory status of each camera. All information was backed up after each session and all memory cards formatted and batteries charged between sessions. All paper records were scanned to create digital records.

Video of each trial was matched to the timing data provided by CA by referencing the GPS time stamp on the timing splits as well as visually identifying the athlete. A log of the trials was created in a bespoke database that enabled the video file, timing data, lane, number of riders in the trial, athlete and bike details to be stored together. The SD cards were then formatted, and any SD cards damaged during the day discarded. A minimum of two hours was allowed for this process.

No biomechanical studies using a database to store kinematics were found in a literature search. As such, a bespoke database was created in Access (Access for Office 365®, Microsoft®, USA). The database stored data analysis parameters for each trial including all the single value kinematic parameters and coaches' parameters. Each trial entry referenced the associated video file so that the video from which a particular value was derived could easily be located and reviewed if desired and analysis easily traced and replicated.

The database allowed easy data filtering and streamlined the process of collating data particularly when dealing with so many variables across 70+ trials. The design allowed easy expansion to add further variables, subject specific parameters, queries and reports. It was constantly updated with the addition of data from each new training session, so statistics could easily be updated by re-running queries. Reports and queries were created using the inhouse wizards.

Chapter 4: Study 1 Determinant Phases of the BMX SX gate start

4. Study 1 Determinant phases of BMX SX gate start action

4.1 Preface

This chapter has been accepted for publication as a chapter in the upcoming book of Biomechanics of Cycling 2nd edition (ed. Bini & Hume). It has been included in its accepted manuscript form in the thesis with permission from the editors (see Appendix 2 for the permission to reprint). Figure and tables numbers and referencing were permitted to match the thesis style. Because the manuscript was reproduced without changes from the accepted version, there is some repetition in content from other chapters in the thesis.

Determinant phases of the BMX SX gate start action
Grigg, J., Haakonssen, E., Orr, R. M., Bootes, W. & Keogh, J. W. L. (In Press) Biomechanics of Cycling (2nd Edn) ed. Bini, R. & Hume, P., Springer, Australia

This research also formed the basis of a presentation at the 2017 Australian Skill Acquisition Network Conference.

Where is time lost in the BMX SX gate start? (presentation)
Grigg, J., Haakonssen, E., Bootes, W. & Keogh, J. W. L. 24 Nov 2017 Australian Skill Acquisition Network Conference, Brisbane, Australia 24-26/11/2017
https://research.bond.edu.au/en/publications/where-is-time-lost-in-the-bmx-sx-gate-start

In order to understand a complex movement, it is necessary to divide the movement into sub-components. While other studies have defined components of the BMX gate start, the literature suggests that these components have not been based on invariant movement based features but rather on events, such as the front hub passing the edge of the gate [14, 38]. This study was designed with the aid of senior CA track sprint cycling coach, Nick Flyger and CA BMX head coach, Wade Bootes. The purpose of Study 1 was to try and clearly identify key phases that can then be reliably used to describe the gate start action in order to provide a foundation for understanding the movement and how it affects the kink time.

4.2 Abstract

The BMX Supercross (SX) gate start performance is a complex action which has been shown to be critical to race outcome. This study sought to define phases of movement of the BMX gate start using the invariant feature, relative time, as per Schmidt's Schema Theory. Ten maximum effort gate starts were performed by each of five Olympic BMX athletes during a pre-Olympic training session on a SX ramp and were recorded with action cameras at 120 fps. The footage was analysed and the movement was divided into six phases. The time spent in each phase was correlated with the ramp kink time split, a common performance outcome measure of gate start performance, for each athlete and for the entire group. Between and within athlete invariance was assessed to quantify invariance. The second crank weight transfer phase correlated most strongly to kink time for the overall sample of five athletes ($r = 0.78$, $p = 0.01$), however, this relationship was highly individual. Clearly defining these phases provides a clear structure around which the gate start can be analysed. Analyses using these phases may improve BMX gate start practice design and the manner in which coaches provide augmented feedback to their athletes.

4.3 Introduction

Bicycle Motocross, commonly known as BMX, has emerged from the world of extreme sports into the Olympic stadium. First appearing at the Beijing Olympics in 2008, BMX Supercross (SX) racing is distinct due to the 8 m high start ramp as shown in Figure 4-1. The ramp leads into a jump and then into a series of four straights consisting of jump and rhythm sections (smaller jumps and rollers) each separated by berms (u-bend corners). A typical BMX track is 300 - 400 m long, with the race generally lasting 25 - 40 s at the elite level. At the start of a race, up to eight riders line up behind the gate in lanes as and a standard warning is announced: “Ok riders, random start, riders ready, watch the gate”. Following the word “gate”, there is a random delay of 0.1 to 2.7 s. This is followed by a sequence of four rapid tones that coincide with a series of signal lights: red, yellow, yellow and green. The gate falls on the last tone and the green light. The riders typically aim to initiate the start action after the red light, meaning that forward motion is occurring before the gate has started to fall. The challenge then is to maintain this forward momentum, while navigating the front wheel over the top edge of the gate without hitting it, and to effectively apply maximum force to the pedals.

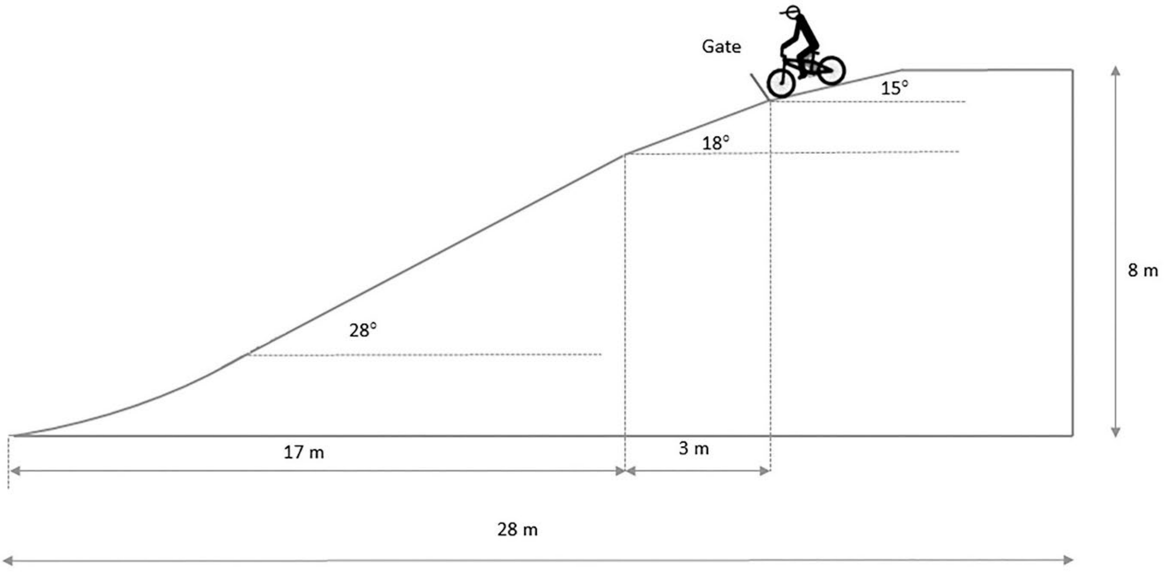

Figure 4-1 Supercross ramp design as specified by the UCI BMX Track Guidelines (Union Cycliste Internationale, 2014a). Not to Scale.

Riders and coaches agree that a competitive advantage is gained by being ahead of the field at the kink (where the ramp changes gradient from 18° to 28°) and at the bottom of the ramp [127-129]. Researchers have also focused on this part of the race as it is known that the rider who reaches the base of the ramp first is able to pick the most advantageous route through the next section and is better able to avoid collisions with other racers [12-14].

The question of how to optimise the performance of the gate start action has been examined in several ways, however an 'optimal technique' has not yet been adequately defined and articulated in the literature. The time split at the kink in the ramp (where the ramp changes gradient, typically 1-1.5 s for elite riders), known as the 'kink time', is often used as a performance outcome for this action, and commonly used in gate start training sessions as a form of augmented feedback [14, 127-129].

Consistent with the lack of information regarding what might be considered 'optimal technique', there is almost a complete lack of scientific data on how the duration of the BMX gate start phases or the movements and body positions inherent to the BMX gate start may influence kink time or any other aspect of BMX performance. Clearly describing and quantifying phases of the BMX gate start using the relative time theory of the Generalised Motor Program, may be useful. This could then be further used to identify factors that are important determinants of performance. Dividing a skill into phases facilitates a greater understanding of the action by identifying sub-movements, degree of variation of spatial and temporal parameters, and the impact each sub-movement may have on the overall performance outcome. This facilitates the design of skill acquisition programs by informing part practice [130] and allows more appropriate augmented feedback and contextual interference to be provided to the athlete [59, 131].

The aim of this chapter was to determine if: 1) the BMX gate start action could be described by a series of distinct phases that exhibit invariant relative timing; and 2) the absolute timing of these phases could be significantly correlated to the kink time. If common phases can be identified within Olympic BMX athletes, then the movement characteristics of each phase can be studied for optimisation in order to better define an ‘optimal’ movement technique. Such phases can also be used to identify relative weaknesses, strengths, movement variation and maturation of developing athletes.

4.4 Methods

4.4.1 Participants

Five Olympic level athletes (three males M1, M2, M3; and two females F1, F2; mean ± SD: 24.1 ± 1.5 years of age) participated in this study. Two of the athletes had previously competed in the Olympic games (London 2012) and all competed in the 2016 Rio de Janeiro Olympics after the data collection took place. All athletes were ranked within the top 20 according to the UCI BMX Racing ranking at the time of data collection. Participants were instructed to wear normal competition clothing and protective wear. Bike setup details, including tyre brand and size, crank length and gearing, were recorded for each participant, and remained the same for all trials. Informed written consent was obtained from each participant in accordance with Bond University's Human Research Ethics Committee.

4.4.2 Procedure

Video data was collected at a pre-Olympic Australian Cycling Team gate training session on a SX track (Sleeman Sports Complex, Chandler, Australia) under the supervision of the team coaching staff in accordance with the methods described by Grigg et al [129]. The Union Cycliste International (UCI) standard BMX SX gate procedure was used [7]. After descending the start ramp, the athletes typically took the first 1-2 jumps and would then taper off and leave the track. This effort represented about a quarter of the complete track. The riders then returned to the start. Rest periods were self-selected and typically ranged from three to 15 minutes between trials. Each athlete performed 10 maximum effort gate starts for analysis.

4.4.3 Equipment

Video was collected using GoPro Hero4 Silver (GoPro Inc., USA) cameras attached to the start ramp structure using mounting brackets as described in further detail by Grigg et al [129]. Figure 4-2 shows the camera placement on the ramp. Video was collected at 120 frames per second (fps) at 720 Megapixels (MP) on a ‘normal’ lens angle setting. All cameras’ clocks and the timing system were set to GPS time to enable synching with the timing data and videos. Class 10 MicroSD cards storing up to 64 GB were used in the Hero4 cameras.

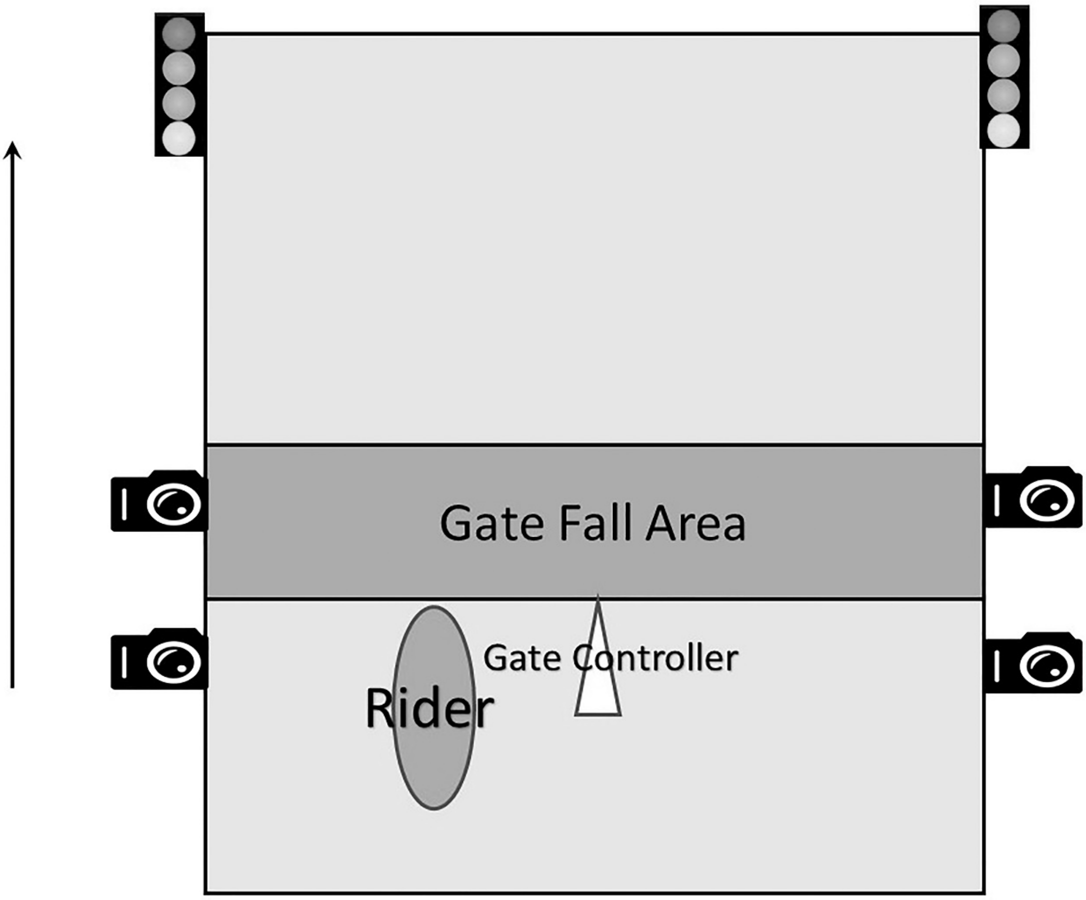

Figure 4-2 Overhead view of the camera setup on the ramp

A Mylaps AMB ChipX (Mylaps Sports Timing, The Netherlands) timing system was used to collect the kink time split for each athlete which was exported into a bespoke BMX timing data logging program (BMX Event Manager Train version 1.3.3). The kink time split starts when the gate begins to fall (on the final light/sound signal). The video files were matched with the kink times using GPS time logs. VideoPad® Professional 4.45 (NCH Software, Inc., USA) was used to edit the video files. In order to measure the duration of each phase, the frame at which each phase began/ended was flagged in VideoPad. Phase timing data was recorded in Microsoft ® Excel 2016 (Microsoft, USA) and intervals calculated. Ten trials for each of the five athletes were analysed.

The same person performed all the analysis in order to negate inter-rater variability.

The phases presented in the current study were based on those defined by Gianikellis et al [38] and Kalichová et al [45] and through consultation with Australian Cycling Team coaching staff.

The phases were defined as follows:

Reaction time (RT). The reaction time phase begins at the start of the first start sound/light and finishes when the first visible body movement occurs.
Slingshot. The slingshot phase begins with the first visible body movement and ends when the crank begins to turn to propel the bike forward. This phase is often used to lift the front wheel off the ground to guide it over the falling gate, and to draw the centre of mass forward to put the body in the optimal position to initiate pedalling. During this phase the athlete and bike may initially travel backwards.
First crank (C1). The first crank phase begins when the crank begins to turn to propel the bike forward and ends when the lead crank reaches the bottom dead centre position (parallel to gravity). During this phase the athlete lifts the handlebars vertically so that the front wheel does not hit the falling gate. By the end of this phase the front of the bike has passed the top edge of the gate as per Figure 4-3.

Figure 4-3 Athlete with right leg lead reaches the end of the first crank and prepares for C2WT.

Crank 2 weight transfer (C2WT). During this phase, which begins with the lead crank at the bottom dead centre position, the athlete transfers weight from the lead leg to the second leg (e.g. right to left leg in Figure 4-3). The cranks rotate 90º from the bottom dead centre position to a horizontal position. The exact crank position at which weight transfer happens varies between and within athletes. The body then needs to self-organise itself in preparation for the power stroke.

Figure 4-4 Athlete with left leg lead has finished C2WT ready for C2PS. The power stroke for C2 is applied with the non-lead leg, in this case the right.

Crank 2 power stroke (C2PS). The athlete applies maximum force to the pedal with the ‘second’ leg [34]. The cranks rotate a further 90º, returning to the vertical position (i.e. the crank of the second pedal is now in the bottom dead centre position).

Crank 3 weight transfer (C3WT). The athlete transfers weight from the second leg to the lead leg. The lead crank travels 90º from top dead centre. During this phase the athletes will invariably pass over the ‘kink’ where the gradient of the start ramp increases.

4.4.4 Statistical analysis

The absolute times for each phase (per trial) were recorded in Excel. The total trial time was defined as the sum of all the phase times. The total trial time was not necessarily equivalent to the kink time; the riders may pass the kink at any stage during the third crank. The relative phase time was calculated by dividing the absolute phase time by the total trial time. Descriptive statistics (means and standard deviations) were calculated for the absolute and relative phase times per athlete, then across all athletes to provide mean group data.

For the phases to be considered invariant, they need to be shown to be invariant within and between athletes. To determine the level of athlete invariance, the variability of the relative time was calculated by using the formula $CV = 100 * \frac{\sigma}{\mu}$ where CV is coefficient of variation, σ is standard deviation and μ is the mean. While some movement variance is expected, if relative time CV is ~ < 25% for a complex gross movement then the phase can be said to be invariant [132, 133].

Further to intra-athlete invariance, the movement also needs to be shown to be consistent between athletes. To demonstrate this a correlation was performed that considered the mean relative time spent in each phase for each athlete. Thus, the mean relative times across all phases was correlated between all athletes to calculate the similarity between the mean relative phases between athletes. A two-tailed Pearson's correlation (r) was performed using Statistical Package for Social Sciences (IBM, USA. version 22) to examine the correlation between athletes for each phase. As per the recommendation of Louis et al [134], $r > 0.9$ was considered invariant.

To identify the phase most associated with kink time, a two-tailed Pearson's correlation was performed in which the correlation between absolute time of each phase and kink time was assessed. This was performed for each individual athlete and across the entire sample of 50 trials. To validate this finding, a Coefficient of Determination (R^2) was also calculated for each athlete and across all data points.

4.5 Results

Table 4-1 and Table 4-2 present the mean absolute and relative time spent in each phase considering the athletes separately and then across all the data. Figure 4-5 shows the phase order and relative time across all 50 trials. The degree of within athlete variability, as quantified by the *CV* is presented in Table 4-3. Table 4-4 presents the Pearson's correlation and R^2 and shows a high correlation between mean relative phase times between athletes ($r > 0.8$) [135, 136]. Table 4-5 presents the correlations between kink time and the absolute time.

Table 4-1 Absolute time (seconds; mean ± SD) per phase for each athlete and the combined group

	Kink Time	RT	Slingshot	C1	C2WT	C2PS	C3WT	TOTAL PHASES
M1	1.204 ± 0.008	0.098 ± 0.043	0.297 ± 0.048	0.358 ± 0.045	0.196 ± 0.02	0.174 ± 0.013	0.152 ± 0.015	1.278 ± 0.025
M2	1.253 ± 0.024	0.094 ± 0.021	0.329 ± 0.035	0.362 ± 0.034	0.179 ± 0.017	0.192 ± 0.011	0.144 ± 0.009	1.303 ± 0.031
M3	1.274 ± 0.013	0.122 ± 0.013	0.309 ± 0.025	0.356 ± 0.025	0.199 ± 0.008	0.182 ± 0.013	0.159 ± 0.024	1.329 ± 0.024
F1	1.314 ± 0.01	0.098 ± 0.043	0.304 ± 0.022	0.325 ± 0.021	0.218 ± 0.01	0.213 ± 0.01	0.141 ± 0.017	1.302 ± 0.054
F2	1.377 ± 0.012	0.095 ± 0.029	0.32 ± 0.02	0.334 ± 0.015	0.227 ± 0.021	0.225 ± 0.024	0.173 ± 0.007	1.377 ± 0.023
ALL	1.284 ± 0.06	0.102 ± 0.033	0.312 ± 0.033	0.347 ± 0.032	0.204 ± 0.023	0.197 ± 0.024	0.154 ± 0.019	1.318 ± 0.047

Table 4-2 Relative time (mean % ± SD) per phase for each athlete and the combined group.

	RT	Slingshot	C1	C2WT	C2PS	C3WT
M1	7.7 ± 3.3	23.2 ± 3.7	28 ± 3.3	15.4 ± 1.7	13.6 ± 1	11.9 ± 1
M2	7.2 ± 1.6	25.2 ± 2.4	27.8 ± 2.8	13.7 ± 1.1	14.8 ± 0.8	11 ± 0.7
M3	9.1 ± 0.9	23.2 ± 2.1	26.7 ± 1.8	15 ± 0.8	13.7 ± 1	11.9 ± 1.7
F1	7.4 ± 3.1	23.4 ± 1.7	25 ± 2	16.8 ± 1.1	16.3 ± 0.9	10.8 ± 1.1
F2	6.9 ± 2	23.2 ± 1.4	24.3 ± 1.3	16.5 ± 1.5	16.3 ± 1.7	12.5 ± 0.4
ALL	7.7 ± 2.4	23.6 ± 2.4	26.4 ± 2.7	15.5 ± 1.6	14.9 ± 1.6	11.6 ± 1.2

Table 4-3 Relative timing variability expressed as a coefficient of variation per phase for each athlete and the combined group

	RT	**Slingshot**	**C1**	**C2WT**	**C2PS**	**C3WT**
M1	43.9	16.2	12.0	11.2	7.8	9.2
M2	22.1	9.5	10.4	8.6	6.0	6.5
M3	10.3	9.2	6.7	5.4	7.6	14.6
F1	42.0	7.7	8.3	6.7	5.6	11.0
F2	29.6	3.4	5.7	10.0	11.0	3.5
Combined	31.6	10.5	10.5	10.9	11.1	10.8

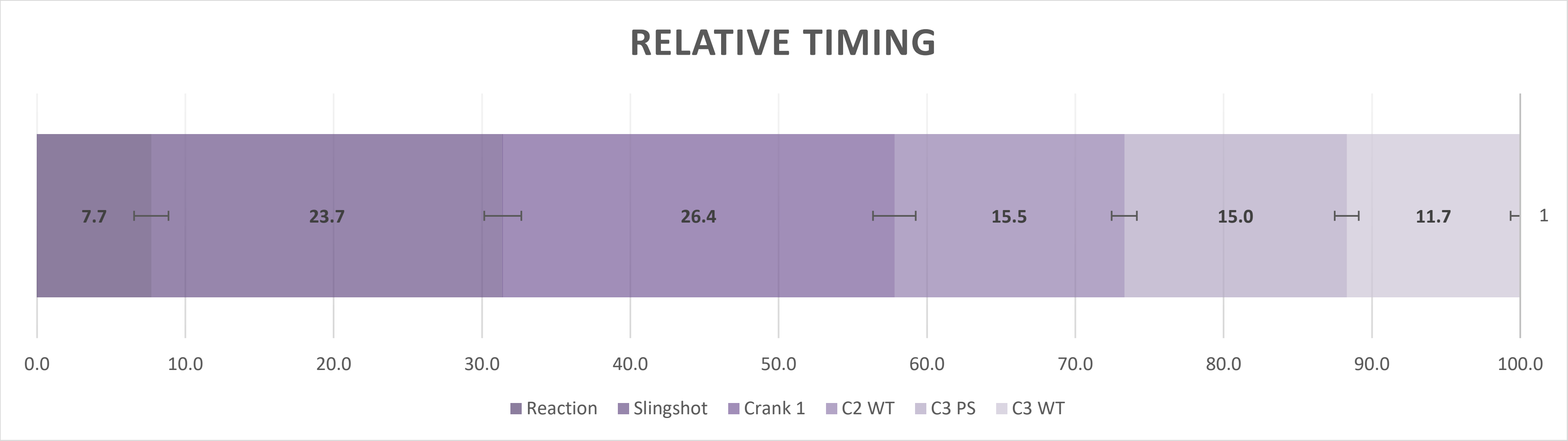

Figure 4-5 Mean relative time spent in each phase across all data with error bars representing standard deviation

Table 4-4 Inter-athlete two-tailed Pearson's correlation

	M1	M2	M3	F1	F2
M1	1	.987**	.997**	.967**	.963**
M2	.987**	1	.992**	.973**	.970**
M3	.997**	.992**	1	.964**	.957**
F1	.967**	.973**	.964**	1	.993**
F2	.963**	.970**	.957**	.993**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 4-5 Pearson Correlation of relative time to kink time per phase for each athlete

	Reaction time		**Slingshot**		**C1**		**C2WT**		**C2PS**		**C3WT**	
	r	R^2	*r*	R^2	*r*	R^2	*r*	R^2	*r*	R^2	*r*	R^2
M1	0.33	0.11	0.09	0.01	-0.60	0.36	0.38	0.15	0.38	0.15	0.00	0.00
M2	0.46	0.22	0.43	0.19	-0.21	0.04	0.57	0.32	-0.04	0.00	0.20	0.35
M3	0.30	0.10	0.37	0.13	-0.29	0.09	0.13	0.02	0.28	0.08	-0.08	0.06
F1	0.56	0.31	0.07	0.00	-0.20	0.04	-0.38	0.14	0.55	0.31	0.57	0.32
F2	0.79**	0.63	-0.18	0.03	-0.21	0.04	-0.44	0.19	0.47	0.22	0.22	0.05
Combined	0.01	0.00	0.17	0.03	-0.39**	0.16	0.78**	0.61	0.76**	0.57	0.34**	0.12

**Correlation is significant to 0.01 (2 tailed), *Correlation is significant to 0.05 (2 tailed)

Shaded cells have significant *r* values and 'large' correlation according to the R^2 value according to literature [69, 137]

4.6 Discussion

Reaction time was the most variable phase (*CV* 44% for M1, 42% for F1). The reaction time in this setting did not involve a choice; just initiation of movement in response to the starting stimulus [138]. Simple reaction processes vary between and within athletes [139], and this was shown in our results where reaction time also had the largest *CV* for each athlete. The BMX gate start action is initiated following a random delay between the set position cue and the starting sound/light. This randomness of the start signal, and the relatively high movement complexity required to coordinate the movements of the body and bike, may also have resulted in greater within and between athlete variation compared to the other phases. It must also be acknowledged that the reaction time could have been defined in a variety of ways for the BMX gate start. In the current study, reaction time was measured as the time between the first start sound/light signal and the first visible movement of the athlete. It is possible that using the first movement of the rear wheel as the end of the reaction time phase may have shown less variation for this phase. It must be noted though, that for most elite riders the first bike movement is backwards, rather than forwards, because of the nature of the slingshot action.

Intra-participant *CV* for relative timing of phases have been previously reported for a variety of human movements. In an investigation of gait, Boudarham et al [140] reported *CVs* of 1.8-3.5% in the temporal parameters for the different phases in walking gait (n = 20, 3 trials). Guarrera-Bowlby et al [141] reported *CV*s for the sit to stand task between 5-10% for adults and 10-18% for children (n= 6 adults, n= 6 children, 30 trials). Galbraith et al [63] reported *CV*s of 7-28% for the duration of block and flight time phases for 12 elite swimmers across 8 trials when performing swimming block starts. What these studies demonstrate, is that for more complex actions such as starts in BMX and swimming, the amount of variation in the temporal measure of sub-movements is larger than for simple or more habitual movements such as walking gait, even in elite athletes. In consideration of this, the *CV*s reported in this study ranging between 3.4 -16.2 % for the movement phases can be reasonably accepted as being relatively invariant [132, 133].

The inter-athlete correlation for the relative timing of these phases was also high and supports linear congruency according to Louis et al [134] as the Pearson's correlation coefficient was over 0.9. The high level of inter-athlete correlation is further evidence to support the proposed definition and relative invariance of the phases quantified in this study. It implies that the five Olympic athletes spend the same percentage of time in each phase as each other – meaning that the relative temporal component of the action is invariant across the phases for all five athletes. According to Generalised Motor Program theory [49], such results suggests that the action is a discrete complex movement and that these phases are a valid description of the movement.

Invariant features describe attractor states of an action [59]. While different phases might be relatively invariant in their relative timing, there may also need to be some movement variability to allow for compensatory adjustments in accordance with changes in the constraints of the athlete, environment and task [142]. In the BMX SX gate start, athletes may experience changes in the constraints underlying the gate start action within a training session and competition. Beyond the random nature of the gate start reaction stimulus, the BMX athlete may experience varying degrees of fatigue, alertness, weather conditions and the number and position of other riders lining up at the gate. The movement generated by the athlete during the BMX gate start needs to accommodate all these between trial differences and adjust accordingly during the preparation and execution of this movement.

In sport, the quantification of sub-movement phase time has been used to determine which part of a complex action is most likely to impact performance outcome [143]. The phases that correlated most strongly with BMX gate start performance (kink time) over the 50 trials for the entire group in the current study were C2 WT ($r = 0.78$ $p = 0.01$, $R^2 = 0.61$) and C2 PS ($r = 0.76$ $p = 0.01$, $R^2 = 0.57$) as shown in Table 4-5. This overall group data demonstrates that 61% and 57% of the variation in kink time for a group of BMX athletes could be explained by variation in the C2 WT and C2 PS phase times, respectively. Such strong findings may suggest that a training focus on these two aspects of the gate start action may improve gate start performance as measured by kink time. As both of these phases involve a highly coordinated production of torques from multiple joints, improvements in these phases may emerge from both biomechanical/skill acquisition as well as strength and conditioning interventions.

Despite a clear correlation between phases and kink time across the group data, only one athlete (F2) had a statistically significant correlation between any particular phase and kink time (Reaction time $r = 0.79$, $p=0.01$, $R^2 = 0.63$). This result suggests that there may be substantial benefit in collecting phase timing data for individual athletes over multiple trials in order to identify the phases that individual athletes exhibit the greatest variability, especially if this variability in phase duration is highly correlated to a performance measures such as kink time.

While Schmidt's General Motor Program does provide a framework for understanding a skill, it does not explain how a skill is learnt [144]. In the present study, it can be seen that a complex task can be divided into components of invariant relative time, which can then be correlated to performance outcome (kink time). Of the six phases defined here, five are movement phases, and the other is reaction time which could be considered separately. A limitation of this study was the small number of athletes, however, given the calibre of the athletes, it was still considered valuable because of the maturity of their technique and the relatively large number of trials per athlete compared to previous work in BMX rider biomechanics such as Kalichová et al [45], who analysed one trial from each of two athletes and Gianikellis et al [38] who analysed one trial from each of three athletes.

4.7 Conclusion

In conclusion, this study shows that the BMX gate start action can be divided into 6 sub-movements, that demonstrate similar degrees of invariance in relative timing (with the exception of the reaction time phase) to that of the sit to stand [141] and swimming start motor skills [63]. From an overall group perspective, the phases most highly correlated to performance outcome were the C2 WT and C2 PS. This contrasted with individual athlete data, whereby one athlete (F2) recorded a significant correlation between any phase and kink time. These results provide some insight into the most important phases of the BMX gate start but do suggest that some aspects of the gate start action are unique to each individual athlete. This supports the use of individualised strategies for athlete training and assessment.

Chapter 5: Study 2 Variation in phasing: is there a difference between men and women, Elite and World Class BMX riders in how the gate start action is performed?

5. Study 2 Variation in phasing: is there a difference between men and women, Elite and World Class BMX riders in how the gate start action is performed?

5.1 Preface

Study 2 is an extension of Study 1. Data from five more athletes were added to the data from Study 1 to enable a comparison of WC and Elite action using the absolute and relative timing of phases. This also meant that the number of males and females was enough to give some indication of potential difference in the gate start action between genders. The methodology was essentially the same as that of Study 1, but the statistical analysis was extended to investigate these questions. This chapter was written to facilitate reading in isolation which meant some repetition including a brief outline of the phases described in detail in Study 1 (Chapter 4).

5.2 Abstract

Do world class (WC) BMX athletes who are regularly seen on the podium have technical skills that differentiate them from their peers? Are differences in muscular strength the only factor differentiating male and female BMX athletes or is there a significant difference in technique? Using determinant phases, differences in the gate start action between five WC and five Elite athletes, and six male and four female athletes, were analysed. The results showed that WC athletes executed the *second crank weight transfer* and *second crank power stroke* phases more quickly and with less temporal variation than the Elite athletes. Male athletes were shown to be consistently significantly faster in the movement phases and showed greater variation in phase duration than females.

5.3 Introduction

In sports like BMX, winning races can lead to increased sponsorship and scholarships from national sporting bodies which enable the athlete to devote more time to training and racing. In BMX Supercross (SX) racing the 300 - 400 m track starts with an 8 m high ramp. Research shows that the athlete who reaches the bottom of the ramp and then lands the first jump in front of the other athletes is most likely to win the race [5]. Athletes who are able to gain a competitive advantage on the ramp, even before the change in gradient (~ 3 m), known as the kink, have a tactical advantage going into the first jump as they are able to select the optimal line and potentially block close competitors from the preferred line into the first jump [127].

Because of the significance of this part of the race, coaches and athletes focus a lot of attention on improving performance of the gate start action. Previous studies have examined different components of the gate start including power production [44, 145-147], kinematics [16, 38, 45, 128, 129] and determinant phases [148]. The study presented here aimed to quantify some of the differences between WC and Elite athletes and male and female athletes performing the gate start action. WC riders were defined as those ranked within the Union Cycliste Internationale (UCI) top 20 and the Elite are those ranked within the UCI top 20-100 at the time of data collection. The phases defined in Grigg et al [129][2] were used as comparator categories, with the difference in absolute time, variation of absolute time, and difference in relative time for each phase being compared between the two groups: WC vs Elite, male vs female.

The gate start action is a distinct complex action that begins with a standard warning, then a random interval that can be between 0.1 – 2.6 s followed by a light/tone stimulus (4 lights/tones each separated by 120 ms) at the end of which the gate drops. On the first light/tone stimulus the athlete reacts and begins to navigate the bike over the falling gate while initiating pedalling. The first action is often referred to as the ‘slingshot’ and forms a propulsive forward thrust during which the bike moves backwards before moving forwards. The set

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[2] As per Study 1 (Chapter 4)

position, as shown in Figure 5-1, has the pedals at an approximately horizontal position. The first crank takes the lead leg to bottom dead centre (6 o'clock'), where each 'crank' is considered to be a crank excursion of 180º. It takes approximately three cranks to reach the kink in the ramp, where the gradient of the ramp changes (from ~ 18º to ~ 28º). The gate to kink time split, referred to as the 'kink time', is commonly used as a performance outcome for feedback during training.

Figure 5-1 standard set position with a right lead leg

Gross et al [16] showed that 'faster' athletes at the base of the ramp have a higher velocity and have travelled further at gate drop than slower athletes. As described in Gross et al [16] the ability to generate high velocity during the gate start is a combination of technical and neuromuscular factors. The study presented in this chapter focussed on the technical aspect of the SX gate start.

Grigg et al [129][3] defined six distinct phases of the gate start action as outlined in Table 5-1. The absolute time spent in each phase was correlated to kink time, with the weight transfer phase of the second crank having the highest correlation to kink time (r = 0.78 p = 0.01, R^2 = 0.61) and the power stroke of the second phase also having a significant correlation (r = 0.76 p = 0.01, R^2 = 0.57) for five WC athletes each performing 10 trials each. Interestingly, while the group summary results clearly showed this correlation, the results for individual athletes showed that each athlete had their own unique correlations between each of the six phases and total kink time.

Table 5-1. Phases definitions

Phase name	Description
Reaction Time (RT)	From first start beep to first visible movement
Slingshot	First visible movement to first forward movement of the crank
First Crank (C1)	First forward movement of the crank to the crank in the vertical position
Second Crank Weight Transfer (C2WT)	Crank vertical → horizontal
Second Crank Power Stroke (C2PS)	Crank horizontal → vertical
Third Crank Weight Transfer (C3WT)	Crank vertical → horizontal

The aim of this study was to determine if there was a significant difference in the relative time spent in each phase during the BMX SX gate start action between WC and Elite athletes, and between male and female athletes. The

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[3] As per Study 1 (Chapter 4)

second aim was to determine if there was a difference in variability of movement between WC and Elite athletes, and males and females. The results from this study may improve coaches' understanding of the critical factors that may differentiate WC vs Elite and male vs female. This may have direct implications to the coaching process, athlete development plans and be used to focus further research into the gate start action.

5.4 Method

All data collection was performed on a UCI standard BMX SX track during a normal training session[4].

5.4.1 Participants

Five Olympic level athletes (three males and two females, mean age 24.1 ± 1.5 years) were recruited from Cycling Australia's BMX High Performance Unit (BMX HPU), in a year prior to the 2016 Olympics. A further three males and two females, mean age 21.4 ± 3.0 years, were recruited from the BMX Australia Development Academy (DA) into the Elite group. All BMX DA athletes had qualified for the UCI BMX SX World Championships in the year of testing. All athletes were instructed to wear normal competition clothing and protective wear and bike setup (including tyre choice and gearing) remained the same for the entire testing session. Written informed consent was obtained from each participant in accordance with Bond University's Human Research Ethics Committee.

5.4.2 Data collection

Video data was collected during a standard gate training session at the Sleeman Sports Complex SX track (Brisbane, Queensland, Australia) under the supervision of BMX HPU staff and coaches. Each participant performed 10 maximum effort gate starts for analysis. After going down the start ramp, the athletes progressed along the track a self-selected distance and then tapered off and returned to the start of the track at the top of the ramp. Rest periods between trials were self-selected and tended to be 3-15 minutes as per Phillips et al [149]. Two GoPro Hero4 Silver (GoPro Inc., USA) cameras were firmly attached to the ramp structure in line with the starting position of the riders and the gate fall area (as shown in Figure 5-2) with the cameras set to record at 120 fps, 720 MP with a normal lens setting and loaded with Class 10 MicroSD cards as validated for measuring kinematics of BMX riders in Grigg et al [129]. A Mylaps AMB ChipX (Mylaps Sports Timing, The Netherlands) timing system

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[4] See Chapter 3 for more detail on training sessions.

was used to record the kink time and timing data were exported to BEM (BMX Event Manager) Train (version 1.3.3).

Figure 5-2 Camera placement on the SX ramp platform

5.4.3 Phase definitions

The phases were defined as per Table 5-1[5]. During the last phase most of the riders passed the kink.

5.4.4 Data analysis

The amount of time spent in each phase was calculated from the video files by marking the frames for the beginning and end of each phase on the video file in VideoPad® Professional (version 4.45 NCH Software, Inc., USA) and recording these timings in Microsoft® Excel 2016 (Microsoft, USA).

5.4.5 Statistical analysis

Ten trials were analysed for each athlete. Absolute and relative times, and coefficient of variation (*CV*) were calculated as per the methodology outlined in Grigg et al [129][6]. Descriptive statistics were performed grouping the athletes all together (*n* = 10), and then dividing them according to performance level:

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[5] As per Study 1.

[6] As per Study 1.

WC (*n* = 5), Elite (*n* = 5) and then gender: male (*n* = 6) and female (*n* = 4). Two-tailed independent sample t-tests (Alpha set at 0.05) were performed in SPSS® (version 22, IBM, USA.) to identify statistical significance in absolute times and the *CV* between male and female, and WC and Elite groups. Finally, a two-tailed Pearson's correlation (*r*) was performed in SPSS to identify the phase most associated with kink time considering the groups separately, and all the data together. Correlations were graded according to literature [137, 150-152]:

- 0 - 0.19 very weak,
- 0.20 - 0.39 weak,
- 0.40 - 0.59 moderate,
- 0.60 - 0.79 strong and
- 0.80 - 1.0 very strong.

5.5 Results

The first aim was to determine if there was a difference in the relative time spent in each phase during the BMX SX gate start action between WC and Elite athletes, and male and female athletes. The mean (± SD) for absolute and relative time per phase for each group, and across all data, are shown in Table 5-2. Figure 5-3 shows the overall difference in phase timing between the sub-groups.

5.5.1 Difference in phases WC vs Elite

The data in Table 5-2 show that while there was no statistical difference in kink time between WC and Elite ($p = 0.62$), there was a significant difference in the absolute time in C2WT (WC 0.204 ± 0.023 s, Elite 0.219 ± 0.028 s, $p = 0.005$) and C2PS (WC 0.197 ± 0.024 s, Elite 0.187 ± 0.025 s, $p = 0.045$). The data in Table 5-2 suggest that the Elite athletes use a shorter slingshot, longer C2WT and shorter C2PS than the WC athletes. The relative times show difference in the RT phase (WC 7.7 ± 2.4%, Elite 6.9 ± 1.7% $p = 0.027$) and C2WT (WC 15.5 ± 1.6%, Elite 16.7 ± 1.9%, $p = 0.001$) but not C2PS ($p = 0.06$). These findings suggest that C2WT is a primary point of difference in the performance of the gate start action between these two groups.

5.5.2 Difference in phases male vs female

The data summarised in Table 5-3 suggested a significant difference in the absolute times in the kink time, slingshot, C1, C2WT, C2PS between the male and female groups. When considering relative time, significant differences were only found for Crank1, C2WT and C2WT with $p < 0.01$ for all three phases. Males performed a longer Crank1 and a shorter C2WT and C2PS than the female athletes.

5.5.3 Variation in movement WC vs Elite

The *CV* for both absolute and relative time was summarised in Table 5-4. A significant difference in movement variation was found during C2PS. This was evident in both absolute and relative measures ($p = 0.039$ absolute time, $p = 0.045$ relative time). On average, Elite athletes had 3.2 ± 1.32% (relative time) and 3.7 ± 1.5% (absolute time) more variation than WC athletes in the C2PS phase.

5.5.4 Variation in movement male vs female

A significant gender based difference was found in movement variation in the slingshot phase (p = 0.013 absolute time, p = 0.012 relative time). On average, males had 5.2 ± 1.4% (absolute time) and 5.4 ± 1.4% (relative time) more variation than females in the slingshot phase.

5.5.5 Correlation to kink time

Correlation between kink time and absolute time for each phase per group was summarised in Table 5-5. This showed an overall ‘moderate’ correlation between kink time and C2WT ($r = 0.58$, $p < 0.01$) and C2PS ($r = 0.55$, $p < 0.01$), a strong correlation between kink time and C2WT ($r = 0.78$, $p < 0.01$) and C2PS ($r = 0.76$, $p < 0.01$) in the WC and then a moderate correlation between kink time and slingshot phase ($r = 0.54$, $p < 0.01$) and C2WT ($r = 0.54$, $p < 0.01$).

Table 5-2 Mean ± standard deviation of absolute times per phase, each of whom performed 10 max effort starts. Significant differences are shaded.

	Kink time	RT	Slingshot	C1	C2 WT	C2 PS	C3 WT	Total
ALL *n* = 10	1.296 ± 0.064	0.096 ± 0.028	0.304 ± 0.045	0.353 ± 0.04	0.211 ± 0.026	0.192 ± 0.025	0.155 ± 0.022	1.313 ± 0.054
WC *n* = 5	1.284 ± 0.060	0.102 ± 0.033	0.312 ± 0.033	0.347 ± 0.032	0.204 ± 0.023	0.197 ± 0.024	0.154 ± 0.019	1.318 ± 0.047
Elite *n* = 5	1.308 ± 0.066	0.091 ± 0.023	0.295 ± 0.053	0.359 ± 0.047	0.219 ± 0.028*	0.187 ± 0.025*	0.155 ± 0.025	1.309 ± 0.203
Males *n* = 6	1.250 ± 0.026	0.098 ± 0.028	0.292 ± 0.048	0.364 ± 0.045	0.199 ± 0.022	0.18 ± 0.018	0.151 ± 0.020	1.287 ± 0.040
Females *n* = 4	1.365 ± 0.036**	0.093 ± 0.029	0.321 ± 0.033**	0.337 ± 0.025**	0.23 ± 0.020**	0.211 ± 0.023	0.159 ± 0.024	1.353 ± 0.047

*significantly different to WC *p* = 0.05, **significantly different to males *p* = 0.05

Table 5-3 Mean ± standard deviation of the relative phase (%) per phase, each of whom performed 10 trials. Significant differences are shaded.

	RT	Slingshot	C1	C2 WT	C2 PS	C3 WT
ALL *n* = 10	7.3 ± 2.1	23.1 ± 3.3	26.9 ± 3.2	16.1 ± 1.9	14.6 ± 1.7	11.7 ± 1.4
WC *n* = 5	7.7 ± 2.4	23.6 ± 2.4	26.4 ± 2.7	15.5 ± 1.6	14.9 ± 1.6	11.6 ± 1.2
Elite *n* = 5	6.9 ± 1.7*	22.5 ± 3.9	27.4 ± 3.7	16.7 ± 1.9*	14.3 ± 1.7	11.8 ± 1.6
Males *n* = 6	7.6 ± 2	22.7 ± 3.8	28.2 ± 3.3	15.5 ± 1.8	14 ± 1.4	11.7 ± 1.4
Females *n* = 4	6.9 ± 2.1	23.7 ± 2.2	24.9 ± 1.9**	17 ± 1.6**	15.6 ± 1.6**	11.7 ± 1.5

*significantly different to WC *p* = 0.05, **significantly different to males *p* = 0.05

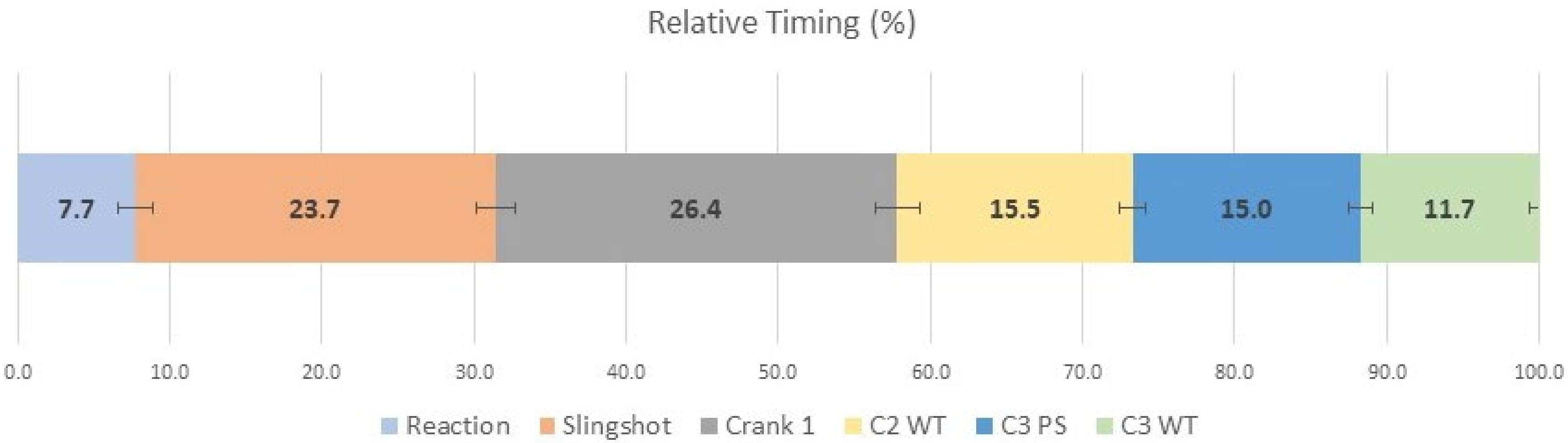

Figure 5-3 Phases of the BMS SX gate start.

Table 5-4 Coefficient of variation across absolute time (s) and relative time (%). Significant differences are shaded.

	ABSOLUTE TIME (%)								**RELATIVE TIME (%)**					
	Kink time	**RT**	**Slingshot**	**C1**	**C2 WT**	**C2 PS**	**C3 WT**	**Total**	**RT**	**Slingshot**	**C1**	**C2 WT**	**C2 PS**	**C3 WT**
ALL n = 10	5.0	29.9	14.9	11.5	12.7	13.2	14.5	4.1	28.9	14.4	12.2	11.9	11.8	12.6
WC n = 5	4.7	32.4	10.6	9.4	11.4	12.3	12.5	3.6	31.6	10.5	10.5	10.9	11.1	10.8
Elite n = 5	5.1	25.4	18.2	13.1	12.9	13.6*	16.3	4.7	24.6	17.4	13.5	11.6	12.2*	14.2
Males n = 6	2.2	28.7	16.7	12.5	11.5	10.1	13.5	3.2	27.2	16.8	11.9	11.8	10.5	12.0
Females n = 4	2.7	31.8	10.4**	7.5	9.0	11.0	15.4	3.5	31.0	9.7**	7.6	9.8	10.6	13.5

*significantly different to WC $p = 0.05$

**significantly different to males $p = 0.05$

Table 5-5 Correlation to kink time for absolute time of each phase per group. Significant correlations are shaded.

	RT	**Slingshot**	**C1**	**C2WT**	**C2PS**	**C3WT**
ALL (n = 10)	0.00	0.35**	-0.25*	0.58**	0.55**	0.24*
WC (n = 5)	0.01	0.17	0.39**	0.78**	0.76**	0.34**
Elite (n = 5)	0.00	0.54**	-0.22	0.54**	0.48**	0.17**
Males (n = 6)	0.20	0.05	-0.05	0.25	0.09	0.12
Females (n =4)	-0.14	0.42**	0.37*	0.15	0.00	0.27

**Correlation is significant to 0.01 (2 tailed), *Correlation is significant to 0.05 (2 tailed)

5.6 Discussion

A significant difference was shown between the WC and Elite BMX athletes in both phase timing and movement variation, and between male and female BMX athletes in both phase timing and movement variation. This suggested a difference in technique rather than just in strength and power.

The data presented here gives absolute times that may be useful to coaches to benchmark athletes. While this performance related data may be collected during training etc., it is often not published. While phases in Study 2 were defined differently to those used in Kalichová et al [45] (1 trial for each of 2 athletes), a comparison is still possible and shows agreeance between data in Table 5-2 and that reported in Kalichová et al [45] as summarised in Table 5-6. Because the total ramp time was used to calculate average ramp velocity in Gross et al [16] rather than kink velocity, again it is not possible to directly compare results.

Table 5-6 Comparison of phase timings with literature.

	Kalichová et al [45] Participant 1	Kalichová et al [45] Participant 2	Study 2 Results (*n* = 10)
Absolute RT (s)	0.069	0.059	0.096 ± 0.028
Relative RT (%)	5.9	5.2	7.3 ± 2.1
Absolute Slingshot time(s)	0.277	0.286	0.304 ± 0.045
Relative Slingshot time (%)	23.8	25.4	23.1 ± 3.3
Absolute C1 time (s)	0.424	0.366	0.353 ± 0.040
Relative C1 time (%)	36.4	32.5	26.4 ± 3.2

5.6.1 Difference in phases

Table 5-2 and the t-test results suggests that the Elite BMX athletes use a shorter slingshot, longer C2WT and shorter C2PS than WC athletes. The implications of this finding relate to the ability to apply power during the power stroke. The slingshot is not only used to lift the bike up to prepare to navigate over the falling gate, but also to prepare for the first crank. It may be that the longer slingshot is used by the WC athletes to a) generate more forward thrust and b) to self-organise into a more advantageous position to begin C1[7].

Gross et al [16] reported significant differences between two groups of BMX athletes titled *faster* and *slower*. In the study by Gross et al [16], it was found that *faster* athletes, that is those with an average ramp velocity 2.47 ± 0.04 $m.s^{-1}$, initiated the first pedal stroke more quickly than the *slower* riders, and with more power [16]. This would suggest that the *faster* riders had a shorter combined RT and slingshot, contrary to the findings of the results presented here which suggested that the faster WC group (WC kink time =1.284 ± 0.060 s vs Elite kink time = 1.308 ± 0.066 s) had a slower RT plus slingshot compared to the Elite group (WC RT = 0.414 s vs Elite RT = 0.386 s). It does however agree with the male vs female findings which show that the slower females (male kink time = 1.365 ± 0.036 s vs female kink time = 1.250± 0.026 s) had a longer RT plus slingshot (male RT = 0.414 s vs female RT = 0.390 s) phase than the males.

Kinematic studies suggest that once moving forward, faster athletes may have greater angular velocity at the knee and hip [16, 45]. This would imply that the faster athletes are moving through the pedalling phases more quickly. Gross et al [16] reported that the *faster* group had a higher cadence (57.6 ± 2.4 rpm compared to 49.5 ± 6.5 rpm) than the *slower* group at the end of C1. Thus, the *faster* group entered the second crank (i.e. C2WT) with a higher angular velocity at the knee and hip joints and a higher crank cadence than the *slower* group. This supports the finding here that the C2WT phase is performed more quickly by the more proficient athletes.

The difference in C2WT has been anecdotally observed by the coaches involved with this study. They suggested that the second crank is viewed as a ‘sticking point’; that it is the ‘tough point’ to push through in the gate start action.

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[7] This was investigated further in Study 5 (Chapter 8).

Some coaches believe that if the second crank is effectively anticipated then the weight transfer from C1 to C2 is better performed and positions the centre of mass behind the front leg ready for maximum application of force during power stroke (W. Bootes, personal communication, 28 August, 2018). Given that this has been suggested based on coaching experience and is now supported through the results of the present study, this was a significant finding and justifies additional focus on this area by coaches and researchers.[8]

In terms of the potential gender difference, a difference in relative timing was not expected as both the males and females share the same coaches and training environment and have a similar training and competition history. The female BMX athletes tended to have a longer slingshot, in both relative and absolute times. A recent kinematic study [153] demonstrated that the trunk lifted 5° more during the gate start in females (n = 4, 3 trials each) than males (n = 6, 3 trials each). This suggests that the female slingshot action may involve lifting the trunk to a more vertical position in order to lift the handlebars to negotiate the falling gate and then re-organise the body to move into the second crank. In contrast the male slingshot keeps the trunk more horizontal and instead may use more shoulder extension and elbow flexion to lift the handlebars [153]. This may be due to greater upper body strength and kinetic chain robustness in males. Increased power in males due to gender associated greater fat free mass has been established in the literature and is to be expected [154]. Focussed training in the area of upper body strength development may create a change in the female action that enables the centre of mass to remain lower, possibly allowing for faster execution of the slingshot[9].

After the slingshot, the females have a shorter C1, then longer C2, in both relative and absolute terms than males. At this stage there is no clear evidence to suggest whether this difference is due to differences in lower body muscular power or technique, or some combination of the two. Investigations into strength training and technique training would be of benefit as they could direct

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[8] It was examined more closely in Study 5 (Chapter 8).

[9] This is discussed further in Study 5 (Chapter 8).

attention to the area(s) most likely to induce significant change in absolute phase times. While roll out factors (tyre, crank, gearing) are known to affect power generation and have been recorded as part of the data collection [145], the pragmatic nature of this research meant that these factors were self-selected by participants as they were preferred for their normal training and competition on the Sleeman track where the testing was performed.

5.6.2 Variation in movement

Variation in movement is expected, and is actually necessary [132]. Changes in movement patterns accommodate environmental adaptations and reduce injury risk [132, 133]. These are described as ‘functional’ variations. Movement variation beyond this may represent an unrefined movement pattern or introduced constraint on the athlete such as fatigue or injury. As such, it is helpful to coaches to be able to define ‘expected’ movement variability.

It is quite clear that for all phases except RT, there was greater variability in the Elite group than the WC group. One reason put forward by the coaches is familiarity with the track and with being ‘under scrutiny’. As with clinical studies, there may well be a ‘white coat effect’ at play for athletes unused to having their actions analysed in detail. The Olympic level athletes had had greater exposure to performance analytics as well as the coaching staff and the SX track which may have given them an advantage in the test environment. Because of the sponsorship and scholarships that delineate WC athletes, they were able to devote more time to training as they did not need to maintain other forms of employment or study. This included not only time on the bike, but complimentary strength training in the gym and sport psychology. In fact, it has been stated that while WC athletes have access to top level coaching, those at lower levels may follow less structured training methodologies and create their own training protocols [155].

The differences found between the genders was not expected. Grigg et al [153] suggested that kinematic data were similar between male (*n* = 6) and female (*n* = 4) BMX riders, so the possible explanation of a larger gross movement in male BMX athletes could not be substantiated at this time. At present there is little research to explain this finding. Horan et al [156] found that movement variability at the thorax-pelvis was greater for skilled females (*n* = 19) than skilled males (*n* = 19) at the midpoint of a golfing downswing and at golf club-ball contact. Further study demonstrated that movement variability in 16 highly skilled golfers did not correlate to performance outcome [157]. Further examination into the kinematics to determine where variation occurred would be necessary to make any further comment on the functionality of the variation reported in Study 2.

5.6.3 Correlation to kink time

The Pearson's correlation to kink time only suggests a strong correlation for the C2 phases for the WC athletes. While other correlations existed, none exceeded 0.8 and as such were not considered strong in accordance with recommendations from literature [137, 158]. Larger sample sizes would give more confidence in the magnitude of these results, but this is challenging due to the small number of WC and Elite athletes available to test and the number of trials that can be collected per athlete at each testing session.

5.7 Conclusion

The study presented in this chapter demonstrates that there was a significant difference in the relative time spent in the C2WT phase during the BMX SX gate start action between WC and Elite athletes, and a difference in the relative time spent in the C1, C2WT and C2PS phases between male and female athletes. Secondly, there was less variability of movement in WC athletes than in the Elite athletes, and less variability in female than male athletes. These results can be used to inform further study in the kinematics of the BMX gate start, enabling the research focus to be more specifically directed to the C2WT phase in male athletes and perhaps to the C1, C2WT and C2PS phases in females. The findings can also be used to inform training and athlete monitoring programs.

Chapter 6: Study 3 Training reaction time to improve BMX SX gate start performance

6. Study 3 Training reaction time to improve BMX SX gate start performance

6.1 Preface

Studies 1 (Chapter 4) and 2 (Chapter 5) demonstrated that the reaction time (RT) phase can account for ~ 7% of the total kink time. Given this finding, it was considered worthwhile investigating methods to reduce RT in an aim to reduce the kink time. This study was facilitated by a grant from the Australian Sports Commission.

Maintaining ecological validity was important in this study so the intervention design encompassed ‘real world’ training environments rather than being laboratory based. The pragmatic nature of this research meant that if the intervention appeared to have a positive effect on the ramp RT and kink time, it could then be applied by coaches and added to an athlete’s training routine. If there were no significant impacts on ramp RT or kink time, the intervention could not categorically be said to be worthwhile in its current format.

6.2 Abstract

Previous studies have indicated that it is possible to reduce race start reaction time (RT) in timed events with a training intervention. A reduction in this RT could prove beneficial to the athlete if it transfers to an improvement in performance outcome. Nine world class (WC) and elite athletes were divided into either a control (*n* = 5) or an intervention (*n* = 4) group. A bespoke RT device was supplied by the Australian Institute of Sport. Baseline RT testing was performed off track using a bespoke reaction timer that used a light stimulus and pressure pedal to measure RT (20 trials) and then on a BMX SX ramp start gate using the same device adapted to measure first rearward movement of the bike after the standard SX gate start signal (5 trials). The intervention group added a RT training activity using the pedal reaction timer to their regular training program each day for two weeks. Both groups repeated the baseline testing after the intervention period. A t-test and Cohens d were used to identify significance and size of change in the pedal RT and ramp RT for each participant and a MANOVA was used to determine significance of inter-group effect. The intervention group significantly decreased pedal RT ($d = -1.14$, $p < 0.01$), but the control group did not ($d = -0.14$, $p < 0.01$). Similarly, the intervention group had a decreased ramp RT ($d = -0.78$, $p < 0.01$) but the control group did not ($d = 0.09$, $p < 0.01$). There was no meaningful change in kink time for either group (intervention: $d = 0.11$, $p < 0.01$, control: $d = 0.13$, $p < 0.01$). The results of this study suggest that further research employing larger sample sizes may be of benefit and support the inclusion of RT training to regular BMX athlete training routines.

6.3 Introduction

The gate start is a critical component of the SX race [127, 153]. The first part of the start action is the reaction time (RT) phase [148][10]. If this time can be reduced, even by 10 ms, then this may enable an athlete to get their handlebars in front of competitors at the kink and thereby take the preferred line over other riders into the first jump. Track position at the first jump is important as the rider who lands the first jump first is most likely to win the race [5]. On this basis, reducing BMX SX race start RT through dedicated training may be of value to the coach and rider.

Previous studies have investigated whether RT can be improved [112, 124, 159]. Madanmohan et al [159] studied the impact of yoga training on auditory and visual simple RT. A 12 week yoga program was shown to decrease visual RT (from 270.00 ± 6.20 ms to 224.81 ± 5.76 ms, $p < 0.01$) as well as auditory RT (from 194.18 ± 6.00 ms to 157.33 ± 4.85 ms, $p < 0.01$) in 27 students. Papic et al [124] used a sport specific auditory stimulus to train start RT in swimmers. A start gun stimulus was added to start training programs for five elite male swimmers in a four-week intervention. Compared to the control group ($n = 5$ elite swimmers), the intervention group saw a decrease in RT of ~ 13 ms ($t = 3.36$, $p = 0.03$). These studies suggest that that RT is a trainable quality that can be reduced with an appropriate intervention.

In the swimming study, Papic et al [124], RT was defined as the time at which the force on a bespoke force plate attached to the start blocks increased above the baseline ground reaction force. This method of change in force measured by a transducer attached to sprint blocks is also used to measure RT for sprinting events in athletics [111, 114, 116, 117, 160, 161]. However, this measure may not reflect the first movement performed by the athlete.

RT is composed of *premotor* and *motor response*[11]. It is recognised that the *premotor response* time is affected by factors including stimulus volume,

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[10] As described in Studies 2 (Chapter 4) and 3 (Chapter 5).
[11] See §2.3.6

duration, predictability of intensity, variation in tone, movement complexity, movement familiarity and sensory integration [59, 102-104], while *motor response* time is consistently variable, that is the coefficient of variation (CV) measured across tests and subjects is consistent [100]. As such, it can be assumed that all measured significant changes that may occur with RT training will reflect improvements in the *premotor response* time. The aim of this study was to determine whether the BMX gate start RT could be improved through specific RT training.

6.4 Methods

As can be seen in Figure 6-1, there are a series of events that make up the start sequence of the BMX race start. The first start stimulus occurs before the race clock starts (i.e. t = 0 s). This means that in terms of race time, RT can be negative as the first functional movement nearly always occurs before the clock starts. In the BMX gate start action, it is the author’s experience that the first visible movement is often a hand or arm movement, but it could also be a change of foot angle. While the first visible movement is typically consistent within an athlete, it can vary greatly between athletes. The first visible movement may actually be a non-functional movement such as a change in head angle. Such idiosyncrasies of the BMX gate start meant that the definition of RT used in this study required considerable thought and discussion. It was decided by the research team that RT would be regarded as the first functional movement defined as when the bike first travelled backwards. This was the functional movement that was considered consistent between athletes and could be easily measured on the track without interfering with the athlete, bike or the track.

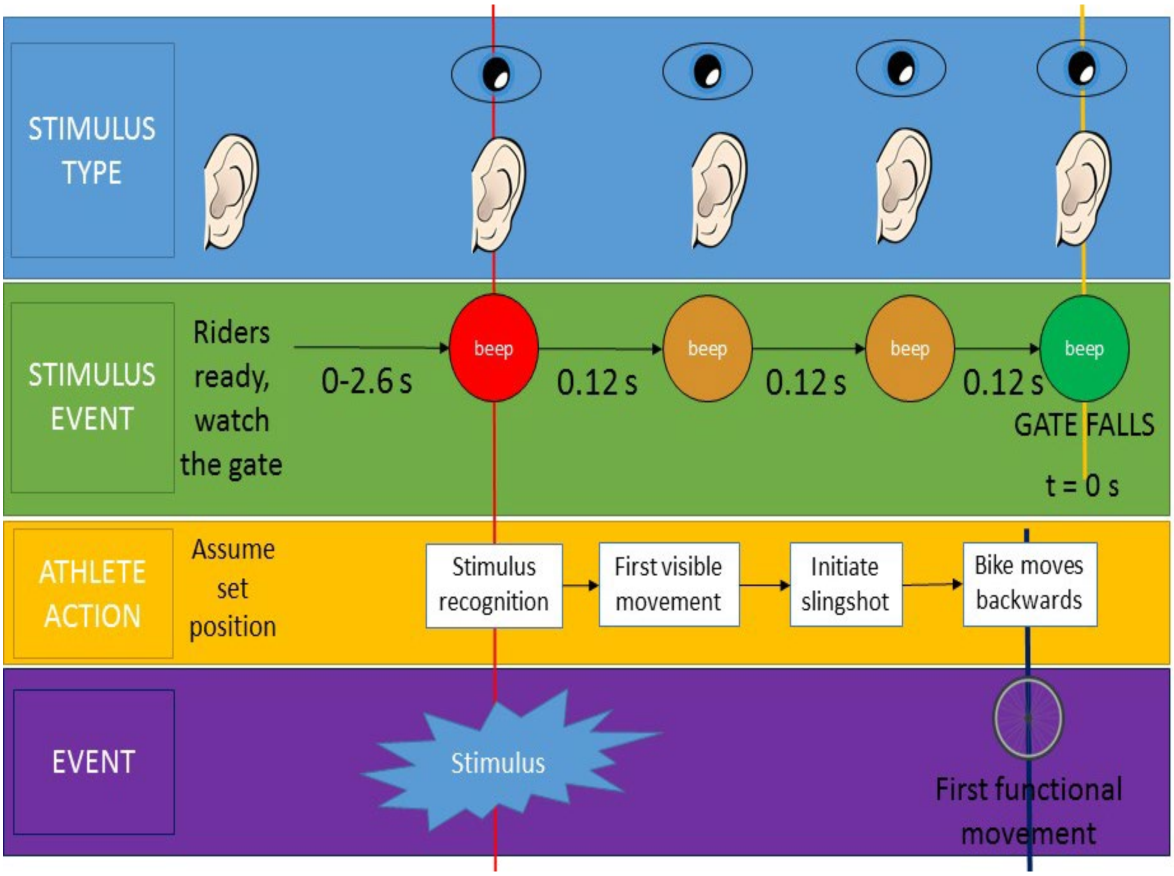

Figure 6-1 Start sequence of events

6.4.1 Participants

Nine athletes were recruited with the assistance of Cycling Australia to participate in the study. One athlete qualified as WC and the others as Elite according to the definition in Chapter 1 of this thesis. All athletes had been competing for at least five years prior to the study and had an average age of 19.7 (± 1.5) years. Participants were split into two groups, intervention and control, with the groups matched for gender, age and experience as much as possible. Athletes were advised not to consume alcohol for 24 hours prior to the scheduled testing and were instructed to wear normal competition clothing and protective wear. The athletes were not paid to participate in the study, but where necessary transport and accommodation costs were paid from an Australian Sports Commission research and development grant. Written informed consent was obtained from each participant in accordance with Bond University's Human Research Ethics Committee.

6.4.2 Procedure

The format of the study consisted of a two part pre-test, two week intervention and a two part post-test which was a repeat of the pre-test as described in Figure 6-2.

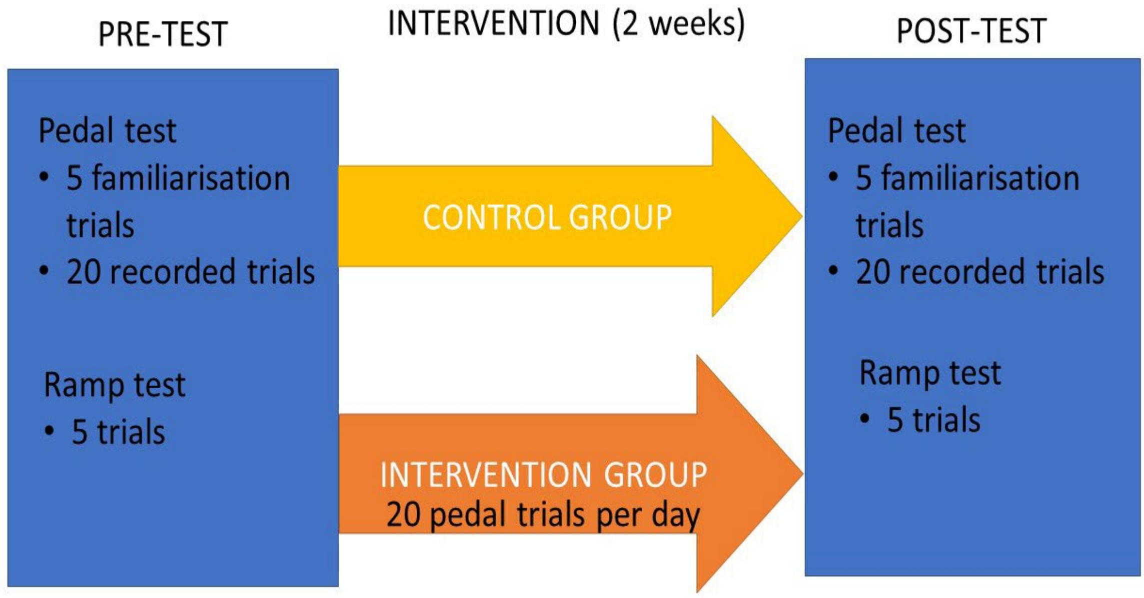

Figure 6-2 Reaction time test format

6.4.2.1 Pedal test

All athletes performed five familiarisation trials followed by at least 20 recorded trials on the bespoke reaction time pedal shown in Figure 6-3 and Figure 6-4. This involved the athlete straddling their own bike, with hands on the handlebars approximating a standing 'set position' as per Figure 6-5. The front wheel of the bike was placed on the pedal. The tester stood ~ 1 m behind the athlete and when the athlete was in position called 'set'. After a tester selected delay of 0 - 3 s, the tester pressed a button on the reaction timing device which sounded a 'beep'. On the 'beep' the athlete lifted the handlebars as rapidly as possible to pull the front wheel off the pedal as per Figure 6-6. The RT measured by the device (in ms) was the delay between the stimulus and the pedal activation. The RT was recorded for each of the trials. Between trials, the athletes were allowed time to reset the bike and themselves. Results were shared with the athletes directly after the 20 trials were completed. The entire test took less than three minutes per athlete and was performed in a quiet room at the Sleeman SX track facility with only the athlete (the subject), the tester and a recorder in attendance.

Figure 6-3 Reaction timer pedal

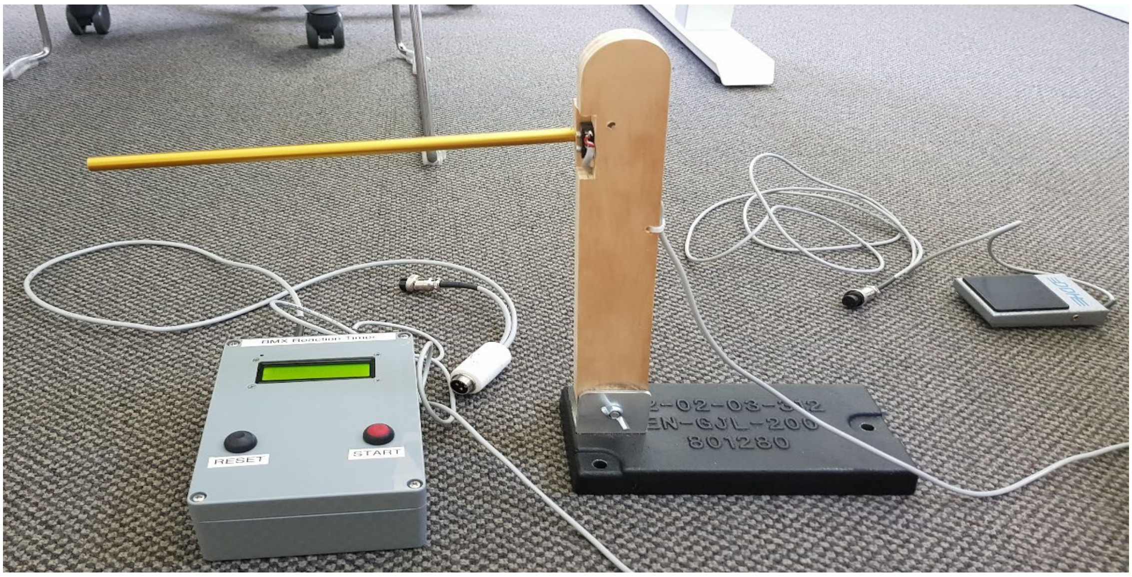

Figure 6-4 Reaction timer controller and display, ramp attachment and pedal attachment.

Figure 6-5 Athlete with the bike on the pedal.

Figure 6-6 Athlete lifts the front wheel off the pedal.

6.4.2.2 Ramp test

After the pedal test, the athletes completed a track based warm up for approximately 30 min before performing a series of gate starts. Each athlete performed at least five maximum effort gate starts using the reaction timer device. The device, as shown in Figure 6-7, was placed on the ramp with the trigger arm resting 5 mm (measured with a jig) behind the rear tyre. When the bike moved backwards, the trigger arm was moved by the rear tyre thereby triggering the RT measurement. On the ramp, the reaction timer was connected to the gate timing system. The ‘start’ of the RT period was defined as the moment when race clock started (t = 0 s) on the green light as per Figure 6-1. As the athlete could move from the first light/tone before t = 0 s (i.e. t = -360 ms), the RT trigger could occur before t = 0 s meaning that the RT recorded on the device could be negative. This was adjusted later considering 360 ms between first (red) and last (green) light/tone. The kink time split was recorded using the Mylaps AMB ChipX (Mylaps Sports Timing, The Netherlands) timing system and BEM (BMX Event Manager) Train (version 1.3.3), BMX timing data logging program.

Figure 6-7 Reaction timer setup on the SX ramp.

6.4.2.3 Intervention

Both groups (intervention and control) performed their routines consisting of track-based, flat sprint and gym-based training during the study. The intervention group performed the RT training each day for two weeks (14 days) in the training environment used on that day as a part of the standardised warm up. The intervention consisted of at least 20 trials using the reaction timer pedal per day for 14 consecutive days (a total of at least 280 reactions). There were four variations of RT training that were randomly used throughout the study:

1. the 'set' call then a random delay of 0 - 3 s then the beep as per the pedal testing (auditory stimulus),
2. instead of calling 'set' the standard BMX SX race start pre-cue of 'Ok riders, random start, riders ready watch the gate' was used before a random delay of 0 - 3 s and then the beep (auditory stimulus),
3. the third variation added the standard SX light sequence to the second variation on the beep (auditory and visual stimulus), and
4. the SX light sequence was used with the standard race start pre-cue, a random delay of 0 - 3 s and no beep (visual stimulus).

RTs were recorded and the athlete was able to view these during and after each session.

6.4.2.4 Post-test

After the two-week intervention period, the initial pedal test and ramp tests were repeated (post testing) by both groups as described in Figure 6-2. This occurred at least 24 hours after the last training session and at the same time of day as the pre-testing.

6.4.3 Statistical analysis

For the pedal RT data, the best trials were retained and low values RT of < 60 ms were removed leaving *n* = 20 per athlete. RTs < 60 ms were deemed to be due to anticipation rather than a true reaction which was considered reasonable based on previous research [107, 110, 126, 138, 159]. Where more than five trials were recorded for ramp RT the best five were selected.

Descriptive statistics were performed on the pedal RT and ramp RT for each athlete and the collated group data. A two-sided simple t-test (*p* = 0.01) and Cohen's d were performed to determine significance and size of effect of intra athlete and inter group (control and intervention) change in ramp RT, kink time (KT), pedal RT before and after the intervention period for all participants. In accordance with Hopkins [162], a d less than 0.2 was considered a trivial effect; 0.2 to 0.6 a small effect; 0.6 to 1.2 a moderate effect; 1.2 to 2.0 a large effect; 2.0 to 4.0 a very large effect; and 4.0 and above an extremely large effect. Significance and confidence intervals were reported. Two tailed Pearson's correlations were performed to quantify relationships between change in ramp RT, change in pedal RT and change in kink time for the individual and pooled data. As per Papic et al [124], Pourazar et al [163], and with consultation with the Bond University bio-statistician a MANOVA was used to quantify between group differences in the outcome measures [164]. All statistics were performed in IBM SPSS Statistics (version 23, IBM, Armonk, NY).

6.5 Results

At baseline, there was no statistical difference between groups in pedal RT (F(1,7) = 1.50, p = 0.26), ramp RT (F(1,7) = 0.60, p = 0.47) or kink time (F(1,7) = 0.47, p = 0.52). The intervention group significantly decreased pedal RT (t (Degrees of freedom) = -7.03, p < 0.01, d = 1.14), but the control group did not (t = -0.97, p < 0.01, d = 0.14). All the intervention participants significantly decreased pedal RT as shown in Table 6-1, but only one of the five control members showed a significant decrease in pedal RT. One member of the control group (CM3) actually showed a significant increase in pedal RT. The difference between the groups' pedal RT at post-test was significant (F(1,7) = 6.03, p = 0.04), with the intervention group having significantly faster (i.e. improved) pedal RT.

After the intervention, the intervention group had a decrease (i.e. improvement) in ramp RT ($t(df)$ = -2.75, p < 0.01, d = 0.78) but the control group did not ($t(df)$ = 0.22, p < 0.01, d = 0.09). As shown in Table 6-1 with the blue highlighting, seven of the nine participants decreased ramp RT. All of the intervention athletes decreased ramp RT with only one athlete showing a significant change, however the control group showed a mixed response, with three athletes decreased ramp RT (one significantly) and the other two increasing RT. After the intervention there was no significant difference between the groups in ramp RT, (F(1,7) = 3.03, p = 0.13).

There was no change in kink time for the intervention group ($t(df)$ = 0.40, p < 0.01, d = 0.11) or the control group ($t(df)$ = 0.33, p < 0.01, d = 0.13). Similarly, there was no difference for the time split taken at the base of the ramp for either group (intervention: $t(df)$ = 0.91, p < 0.01, d = 0.28, control: $t(df)$ = 0.26, p < 0.01, d = -0.02).

Across all participants, there was a decrease in ramp RT (7.2 ± 11.1 ms), pedal RT (11.5 ± 17.9 ms) and an increase in kink time (24.4 ± 92.5 ms). The change in kink time did not correlate to a meaningful change in ramp RT (r = 0.27) or change in pedal RT (r = -0.21). There was a weak correlation between change in ramp RT and change in pedal RT (PCC = 0.48) [69, 137]. Across all data ($n = 90$), the Pearson's correlation between ramp RT and kink time was $r = 0.21$ ($p < 0.05$), suggesting that ramp RT was not highly related to kink time.

Table 6-1 Pre-post reaction time on the ramp, pedal and kink time for all participants Ave ± SD

	Pre Pedal RT (ms)	Post Pedal RT (ms)	Effect size d	Pre Ramp RT (ms)	Post Ramp RT (ms)	Effect size d	Pre Kink time (s)	Post Kink time (s)	Effect size d
CF1	185.3 ± 15.6	195.7 ± 11.4	-0.76	261.0 ± 14.3	272.6 ± 15.1	-0.79	1.382 ± 0.021	1.257 ± 0.009**	7.37
CF2	201.2 ± 19.0	202.6 ± 9.2	-0.09	258.6 ± 2.7	250.8 ± 7.5	1.38	1.385 ± 0.006	1.386 ± 0.016	-0.08
CM1	214.6 ± 18.3	177.6 ± 11.7**	2.41	276.8 ± 3.1	269.6 ± 7.6	1.24	1.274 ± 0.006	1.382 ± 0.021*	-6.99
CM2	207.1 ± 14.5	202.7 ± 18.7	0.26	282.2 ± 9.3	290.4 ± 5.7	-1.06	1.241 ± 0.015	1.395 ± 0.018*	-9.30
CM3	145.7 ± 15.7	157.7 ± 5.6**	-1.02	228.0 ± 11.6	211.8 ± 6.1**	1.75	1.249 ± 0.013	1.385 ± 0.006*	-13.43
C Ave	190.8 ± 29.6	187.2 ± 21.1	0.14	256.7 ± 13.3	270.85 ± 16.9	-0.93	1.254 ± 0.069	1.326 ± 0.069	-1.04
IF1	171.6 ± 14	137.7 ± 25.7**	1.63	260.6 ± 5.9	237.0 ± 9.2*	3.05	1.335 ± 0.006	1.274 ± 0.006*	10.17
IM1	171.7 ± 10.6	155.9 ± 20.1**	0.98	263.8 ± 8.1	250.8 ± 14	1.14	1.257 ± 0.009	1.265 ± 0.020	-0.52
IM2	191.6 ± 15.7	169.5 ± 12.9**	1.54	225.0 ± 13.0	209.4 ± 9.1	1.39	1.261 ± 0.02	1.274 ± 0.005	-0.89
IM3	183.3 ± 7.7	169.4 ± 14.8**	1.18	226.2 ± 5.8	219.4 ± 22.5	0.41	1.263 ± 0.012	1.248 ± 0.014	1.15
I Ave	179.5 ± 16.7	158.0 ± 23.1**	1.06	240.7 ± 19.9	225.7 ± 18.7	0.78	1.273 ± 0.033	1.277 ± 0.040	0.11

C – control group, I – intervention group, M – male, F – female. Blue is a decrease in time (improvement), yellow is an increase.

*statistically significant pre-post difference $p < 0.05$, **statistically significant pre-post difference $p < 0.01$

Figure 6-8 and Figure 6-9 show that the mean of the change in both ramp and pedal RT are positive for all intervention group members, while for the control group the response is mixed, suggesting the presence of a positive effect in the intervention group. This was not however reflected in kink time (see Figure 6-10) which shows a more varied response across all participants, although the intervention group remain closer to a null difference than the control group.

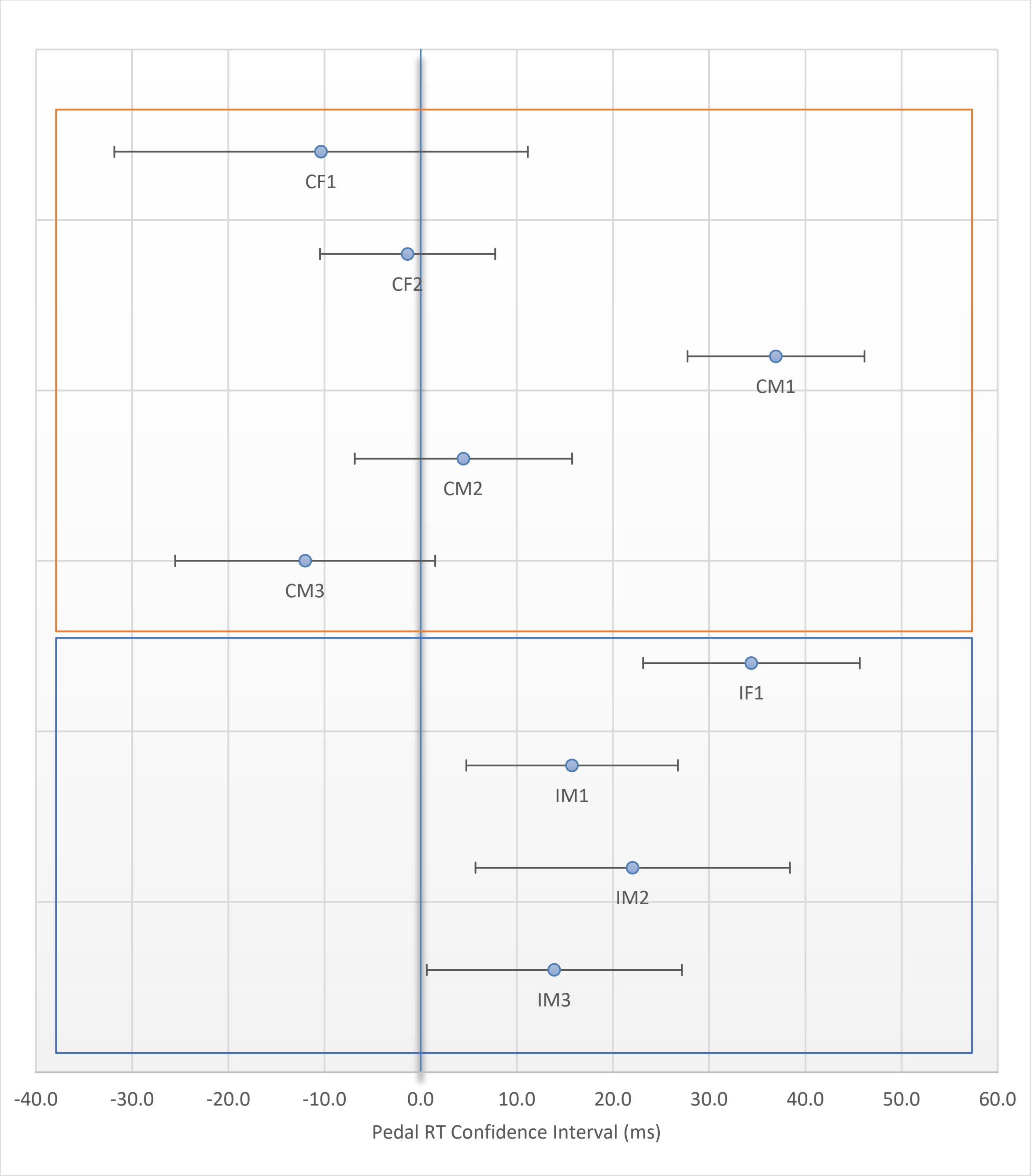

Figure 6-8 Confidence interval of change in Pedal RT for all participants. Positive indicates an improvement in performance.

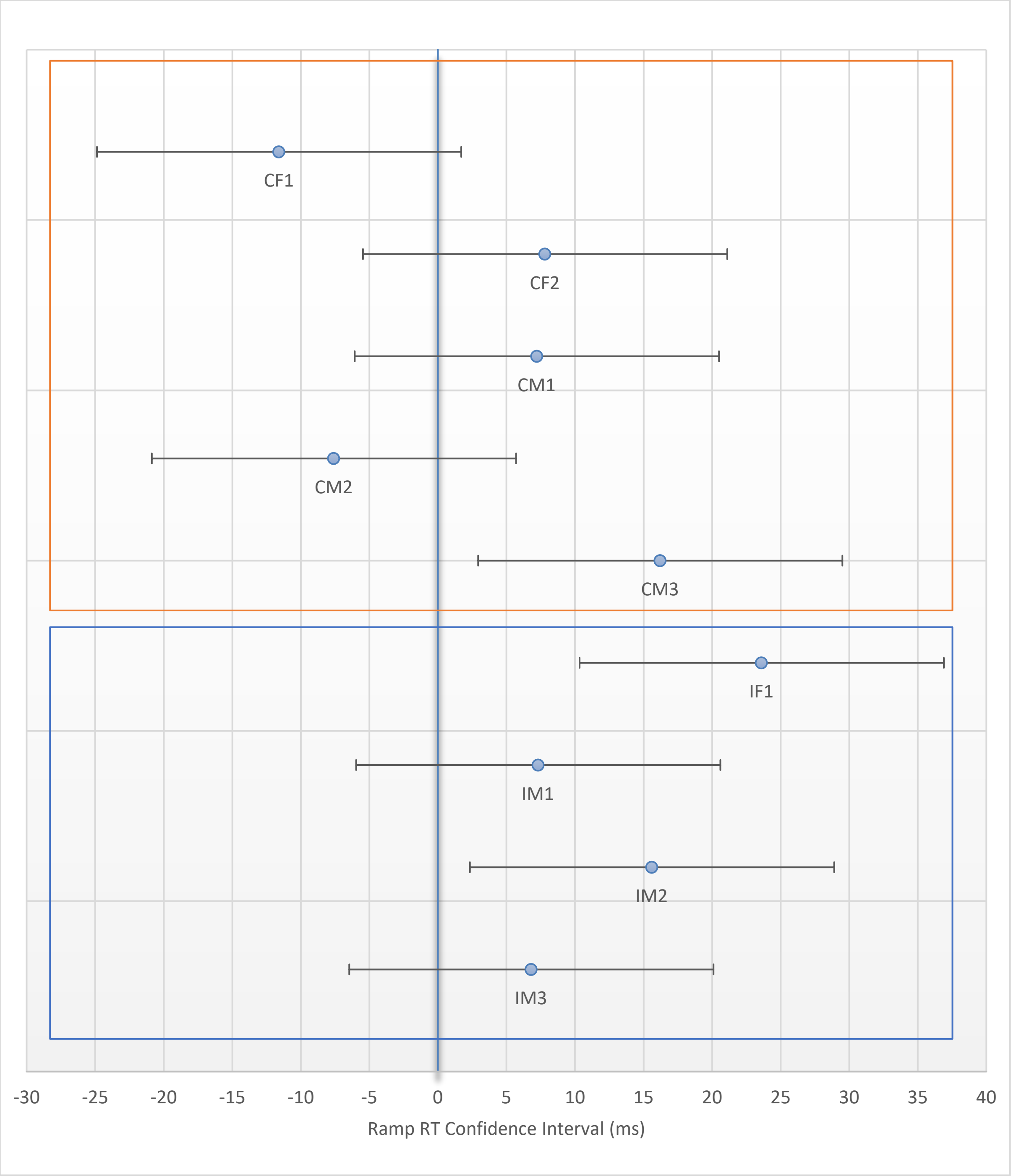

Figure 6-9 Confidence interval of change in Ramp RT for all participants. Positive indicates an improvement in performance.

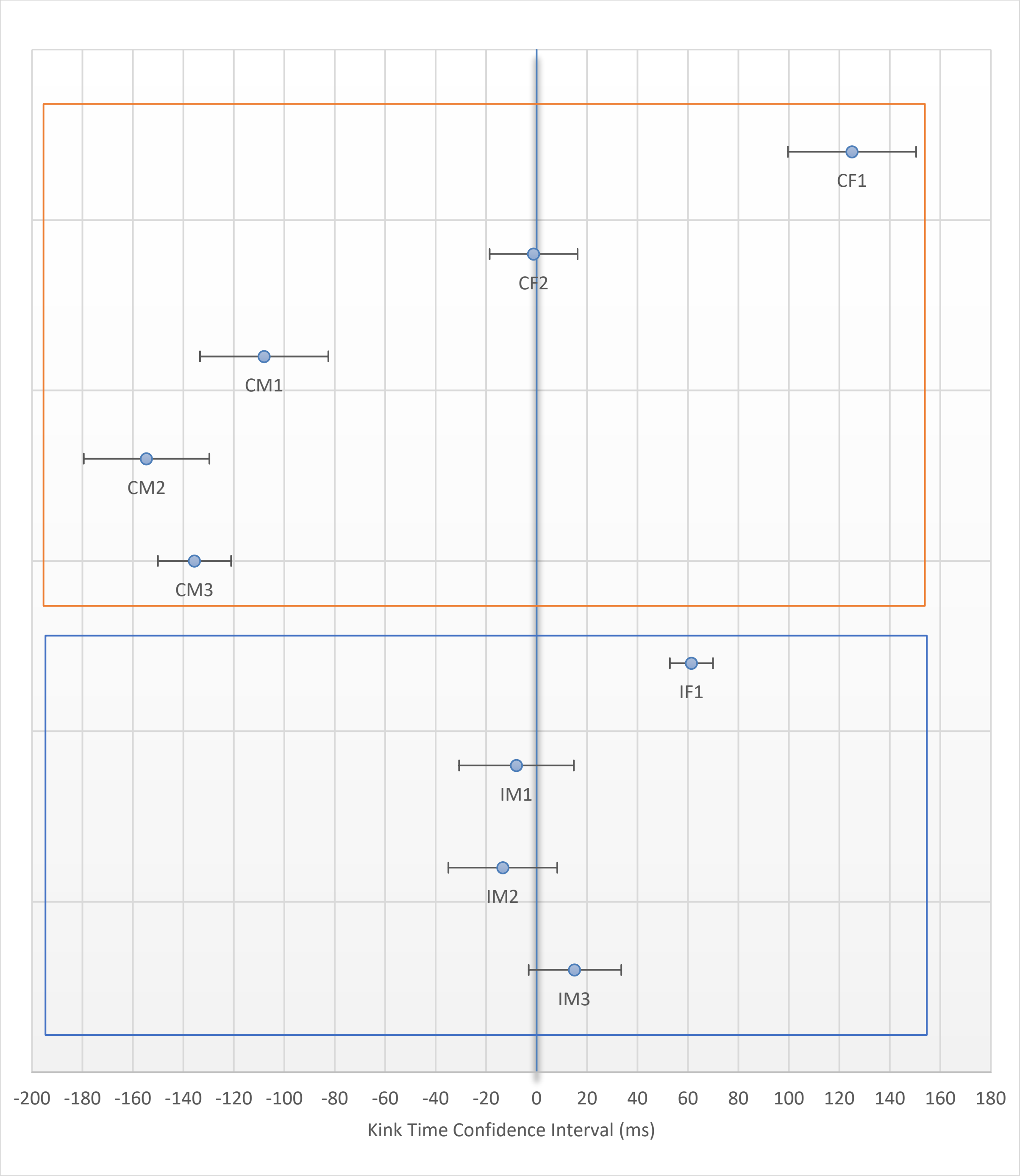

Figure 6-10 Confidence interval of change in Kink time for all participants. Positive indicates an improvement in performance.

6.6 Discussion

The aim of the study presented in Chapter 6 was to determine the effect of a two week RT training intervention on the pedal RT, ramp RT and kink time of WC and elite BMX athletes. The intervention had a moderate to large beneficial effect across the BMX athletes pedal RT ($d = 0.98 – 1.63$ as per Table 6-1) [69, 137]. Considering that the change in pedal RT was significant for all intervention group participants, this intervention can be considered to have had a beneficial effect on the pedal RT for this group of athletes. The small sample size restricts the ability to make a greater generalisation, but these findings warrant further investigation.

The control group had mixed results across all three measures, pedal RT, ramp RT and kink time. Three of the control participants had no significant change in pedal RT. At an individual athlete level, CM2 had a significant decrease in pedal RT but a non-significant decrease in ramp RT, while CM3 had a significant increase in pedal RT but a significant decrease in ramp RT. Overall, the control group showed a trivial non-significant decrease in pedal RT (190.8 ± 29.6 to 187.2 ± 21.1 ms, $d = 0.14$), with a moderate increase in ramp RT (256.7 ± 13.3 ms to 270.85 ± 16.9, $d = 0.93$). This increase in ramp RT may have been due to other influences such as a different level of arousal or surrounding noise levels [102, 120, 165]. The average kink time had a much larger increase (1.254 ± 0.069 ms to 1.326 ± 0.069 ms, $p < 0.01$, $d = 1.04$). This could indicate that the entire performance of the gate start action was slower by the control group at the post-test session which is also suggested by the slower kink times by four of the five control athletes.

All of the intervention group athletes demonstrated a moderate to large significant decrease in pedal RT with a moderate decrease across the whole group (179.5 ± 16.7 ms to 158.0 ± 23.1 ms, $p < 0.01$, $d = 1.06$). All intervention group athletes decreased ramp RT with moderate to very large effect, but only IF1 had a significant reduction in ramp RT (260.6 ± 5.9 ms to 237.0 ± 9.2 ms, $p < 0.05$, $d = 3.05$). This suggests that the intervention had a large effect on pedal RT and moderate to large effect on ramp RT. However, across the group the kink time remained virtually the same at post-test (1.273 ± 0.033 ms to 1.277 ± 0.040, d = 0.110), suggesting that there was no meaningful transfer to kink time.

The RTs measured in the study presented here are in line with those presented in similar sports start RT research as shown in Table 6-2. There is a distinct difference between the RT recorded as a measure of back wheel movement on the ramp (250 ± 26 ms) and the first movement of athletes (91 ± 23 ms). This reflects the different definitions and measurement techniques. In Study 2, the RT is the measured as the time from the start signal to the first visible movement. In the track sprints [114], the RT is measured as the time from start signal to register a 20kg difference in the force on the sprint blocks. In the swim starts [124] ,the RT is measured as the time from the start signal to the first change in force measured on the start blocks. These different definitions make comparing published results challenging.

Table 6-2 Comparison of RTs measured in a sample of sport start studies

Context	RT Mean ± SD (ms)	n	source
Ramp RT	250 ± 26	9	Study 3
Pedal RT	180 ± 26	9	Study 3
Ramp first movement RT (WC athletes)	102 ± 33	5	Study 2
Ramp first movement RT (Elite athletes)	91 ± 23	5	Study 2
100m track sprint	184 ± 22	50	Delalija et al [114]
200m track sprint	212 ± 45	38	Delalija et al [114]
400m track sprint	281 ± 68	35	Delalija et al [114]
Swim start (start training group)	140 ± 9	5	Papic et al [124]
Swim start (start and RT training group)	131 ± 14	5	Papic et al [124]
Swim start (control group)	122 ± 20	6	Papic et al [124]

The use of force plates on the BMX ramp to detect movement based changes in GRF was not feasible given that the riders balance on the two wheels on the bike during the start process, potentially moving continuously and may record a false RT. The rearward movement, or 'recoil', is an important aspect of the start action but varies between athletes[12]. Athletes using 'minimal rear movement' may produce significantly different results to those with a large recoil and may trigger the RT device used in this study later than others, if at all, particularly if they only move back 1-2 mm.

The findings of this study are consistent with other studies that show a decrease in RT where the intervention is specific to the mode of measurement but may not transfer to other applications [124, 125, 165]. For example, Ando et al [125] showed a significant decrease in RT in a button pushing task. Two groups each of eight subjects trained for three blocks, five days a week for three weeks. One group trained with a visual stimulus located in the centre of their visual field, and one with the visual stimulus located in the far periphery of their visual field. The two groups both decreased RT after the intervention period for a visual stimulus where the test condition mimicked the intervention condition (178 ± 9 ms to 167 ± 14 ms, n= 8 central vision group and 195 ± 15 ms to 174 ± 11 ms, n = 8 for far vision group). While there was a reduction in RT for the same task, with different stimuli condition (e.g. a far periphery visual stimulus for the central visual stimulus group etc.) this reduction was not as large or significant as when the training matched the test condition. This suggests that training to match the test conditions is the most efficient way of reducing RT, however some crossover to a similar stimulus condition can be expected [125].

If the training protocol did transfer to ramp RT and kink time, as is desirable for competitive advantage, there would be distinct benefits for athletes. Only three of the participants (one in the intervention group and two in the control group) have regular (weekly) access to the Sleeman SX ramp. Some of the study participants had no local SX ramp, but only 5 m or smaller ramps due to their training location. If a strong consistent transfer of the pedal RT training effect

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[12] As discussed further in Study 5 (Chapter 8).

could be seen on the ramp, this would show that the relatively easy training method could be a useful addition to a daily routine, however only a moderate correlation [137, 151] was seen in the change in ramp RT and change in pedal RT ($r = 0.48$) with no significant change in kink time. A greater number of ramp trials and participants would be preferable to investigate the evidence of a statistically significant correlation.

There appeared to be no transfer to the kink time in the present study, a result similar to Papic et al [124] where the RT intervention training did not appear to transfer to the block time in the swim start. As shown in Study 1 and 2, the RT only represents about 7% of the entire start action [148]. A reduction of 10 ms in this phase may be absorbed by natural variation in the subsequent phases. As seen in Study 2 and 3 the variation in RT can be quite large (RT phase 0.096 ± 0.028 ms for $n = 9$, CV 44% for M1 for $n = 6$, 42% for F1 for $n = 4$). Due to the somewhat high relative variation in RT and likely small absolute reductions in RT that may be observed after two weeks of training, it is possible that a longer intervention may be required to observe a greater effect. It is also possible that some athletes may be further from their RT ceiling than others, enabling greater capacity to reduce RT with training. The understanding of the capacity to train RT is still in its infancy [110], but further research in this area may help determine which athletes are most likely to benefit from RT training. Future research could also investigate whether athletes who have particularly slow RT or variable RT are more responsive to RT training than those who already react quickly and consistently.

Retention of the effect of the pedal RT intervention is unknown. The athletes were only available to attend the training camp for two weeks which limited the intervention period and the ability to perform a retention test. Retention has been tested in perturbation based balance RT training for falls reduction among older adults [173]. It was noted that long term effects on RT were based on perturbation type, magnitude and training load [173]. Retention periods of up to 12 months were reported in the laboratory based study for healthy adults [173]. A study in sufferers of Parkinson’s disease showed an improvement in simple RT with nine Parkinson’s affected and nine healthy adults after a one week intervention [176]. The intervention was done by all participants and involved 120 repetitions of a reaching task on a visual stimulus which was done each day for seven days. After the first day of intervention training, a significant decrease in RT was observed for both groups (*p* = 0.01), with the participants affected by Parkinson's disease decreasing in average RT from 115 ms to 78 ms. At the end of the intervention week a further decrease was seen but this was only significant in the healthy group (*p* = 0.01). A week later, a retention test was performed which continued to show a significant decrease from the baseline test for both groups suggesting a retention affect. This study showed that the majority of the learning effect happened early on in the intervention, continued and was retained for a week post-training. Future research could investigate the long term effect of such learning and whether training for maintenance of the effect was required.

Study 3 indicates that a RT training program can significantly reduce pedal RT (as performed in the training task) and may have benefit in reducing gate start RT in some athletes. Given that the RT training program was easy to implement and that it could be applied by the athlete with off the shelf RT measurement devices, RT training can easily be added to an athlete's training program. Some BMX athletes already use a smart phone application that mimics a standard SX gate start call in gym training as a start signal to begin a lift/jump etc. While no specific cross over has been shown for this gym based application, studies such as the work by Rostami et al [166] suggest that the sheer volume of training may prove advantageous.

6.7 Conclusion

Study 3 presents evidence that a RT training program could be used to improve pedal RT. While the results suggest a trend towards improvement in ramp RT and a translation to improved performance, further research with larger sample sizes and investigating RT change retention would be of value. For athletes with a slow or variable RT adding an RT training activity to the regular training routine may be worthwhile, however individual athlete responsiveness to RT training requires further investigation.

Chapter 7: Study 4 Validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX SX gate start

7. Study 4 Validity and intra-tester reliability of markerless motion capture to analyse kinematics of the BMX SX gate start

7.1 Preface

This chapter is derived from an article published in Sports Biomechanics on 13 Nov 2017 available online: ttp://wwww.tandfonline.com/10.1080/14763141.2017.1353129. Reprinted with permission.[13] See Appendix 3 for more details on reprint permission.

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It was a condition of reprint that the manuscript be presented in its accepted version. As such the only changes are to associated referencing format heading, table and figure numbers so that they match the general thesis format.

This study was undertaken to provide a methodological approach that ensured that the data collected for Study 5 (Chapter 8) could be considered valid and reliable. A kinematic measurement methodology was sought that was easily replicable by coaches, and could be portable to, and employed on, different tracks.

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7.2 Abstract

The aim of this study was to quantify the validity and intra-tester reliability of a novel method of kinematic measurement. The measurement target was the joint angles of an athlete performing a BMX SX gate start action through the first 1.2 s of movement in situ on a BMX SX ramp using a standard gate start procedure. The method employed GoPro® Hero 4 Silver (GoPro Inc., USA) cameras capturing data at 120 fps 720 p on a ‘normal’ lens setting. Kinovea 0.8.15 (Kinovea.org, France) was used for analysis. Tracking data was exported and angles computed in Matlab (Mathworks®, USA). The gold standard 3D method for joint angle measurement could not safely be employed in this environment, so a rigid angle was used. Validity was measured to be within 2º. Intra-tester reliability was measured by the same tester performing the analysis twice with an average of 55 days between analyses. Intra-tester reliability was high, with an absolute error < 6° and < 9 frames (0.075 s) across all angles and time points for key positions, respectively. The methodology is valid within 2º and reliable within 6° for the calculation of joint angles in the first ~ 1.25 s.

7.3 Introduction

Bicycle motocross, BMX, was developed in the 1960s in the USA as an alternative to motor cross racing [1]. BMX Supercross (SX) racing existed outside the mainstream sporting world until its inclusion in the Olympic games in 2008 [1]. SX tracks are distinguished primarily by an 8 m high start ramp. While start ramps vary subtly in height, width and gradient, the SX ramp initial gradient must be ~ 18° until a change in gradient, referred to as the 'kink', at ~ 3 m where it changes to ~ 28°[7]. Tracks range in distance from 300 – 400 m and consist of straights including jumps, pump or rhythm sections, and berms (u-shaped corners) [6]. BMX racing has a unique start procedure. Eight riders line up behind the gate in lanes as per Figure 7-1. A standard warning is announced: 'Ok riders, random start, riders ready, watch the gate'. Following the word 'gate' there is a random delay of 0.1 to 2.7 seconds. This is followed by a sequence of four rapid tones that coincide with a series of red, yellow and green lights. The gate falls on the last tone and light; however, the riders can react and begin the start action when the first tone sounds.

Figure 7-1 Riders lining up at the start gate on the BMX SX ramp used for data capture. Source: Photo by author.

Riders and coaches agree that a competitive advantage is gained by being ahead of the field at the bottom of the ramp, preferably at the kink. The first rider to the base of the ramp is able to pick the most advantageous line through the next section and is better positioned to avoid collisions with other riders [12, 13, 167]. A study investigating placings from four time splits during four World Cup events in 2012 (in Canada, Holland, Norway and USA) showed a significant positive Kendall's tau-b bivariate correlation (τ=0.586, P<0.01) was found between riders placed 1st, 2nd and 3rd at the first split (on the start ramp), and those placed 1st, 2nd and 3rd at the end of the race [5]. Ranking highly in each race is critical. Riders must achieve a top 4 result in each qualifying round in order to proceed to final rounds. They must then place in the top 4 within each final round to progress to the main final. This combined with the strong correlation between placing on the ramp and final placing within each race, justifies a strong training focus on maximising gate start performance. According to the BMX Australia High Performance Unit (BMXA HPU) Head Coach, approximately one third of training time on the track is focused on gate start technique and much of the strength and conditioning program revolves around improving the physical capacities required for the start action (W. Bootes, personal communication, May 16, 2016).

While preliminary studies have described gate start kinematics of BMX riders [38, 45], little attempt has been made to correlate rider kinematics to BMX performance outcome measures. In BMX gate start training, a key performance indicator is the time taken to reach the kink from the start, referred to as the ‘kink time’. Knowledge of performance feedback has been shown to improve kink time in BMX, yet there is little evidence on which to base quantitative performance feedback [14]. More complete investigation into rider kinematics could identify key biomechanical variables that relate to performance outcomes such as kink time. Range of motion and spatio-temporal aspects, such as the relative timing of joint movements during the gate start action, could be valuable coaching tools if correlated to performance outcomes.

Motion capture is one of the most commonly used methods for collecting kinematic data in sports kinematic analysis. It is typically done by placing markers on the participant and then translating the marker movement into a 2D or 3D coordinate system. Research has shown that for movements predominantly in one plane, such as cycling, 2D video analysis correlates well to the more complex and expensive method of 3D analysis [10, 168-170].

Markerless motion capture in situ is becoming more common in field-based sports research [80, 81, 83, 85, 171, 172]. Coaches have increasingly been using video to provide their athletes knowledge of performance feedback, particularly since the invention of devices such as the iPad (Apple Inc., USA) [173]. Applications such as a bespoke golf swing analysis tool have been validated in literature [80], which was found to have a tracking accuracy of 96%. Coach's Eye has also proved very popular with coaches for amateur and professional sports training [173] and has been validated for use in clinical settings [174]. These tools are popular low cost solutions for providing immediate quantitative feedback to athletes during training and/or competition. What is missing in sports such as BMX SX riding, is the movement characteristics that provides optimal performance outcomes and benchmarks for athlete development.

Markerless motion capture allows for the activity to be performed under conditions that closely resembles a competition environment. In the case of BMX SX, a rider is able to use standard safety clothing, a regulation BMX bike, an Olympic standard start gate. Environmental constraints such as weather, competition pressure and equipment can be similar to that experienced in competition. An important consideration in measuring BMX athlete movement is the high level of inherent danger in the activity [20, 21]. An athlete preparing to undertake a maximum effort gate start is at a high level of arousal and can be easily disturbed by changes in physical sensation that are outside of their experience. This means that a change from their standard baggy clothing to form fitting clothing, adding measurement devices such as accelerometers or electromyography units to the body, can off distract the rider and increase the danger level as well as precipitate a change in action. Several of the athletes approached as part of this study were reticent to have any form of marker added to their clothing. BMX Australia requires that the standard safety clothing

be worn at all tracks in Australia, thereby minimising alteration to clothing [175]. The safety regulations include the application of a non-lycra containing jersey over the safety equipment such as elbow pads etc. These restrictions make the methodological options for movement analysis quite limited.
It is important to take kinematic measures for sporting activities in situ, as studies have shown, laboratory results do not always correlate to on-field performance [51, 54, 86]. The increasing use of markerless motion capture in the field and the potential for substantial differences in outcomes between field testing and laboratory testing highlights the need for valid and reliable in situ kinematic measurement methodology.

Multiple cameras with high speed frame rate (≥ 60 frames per second (FPS) and high definition picture quality of at least 720 p (1280 x 720 px) in conjunction with motion analysis software packages have been shown to be valid for the analysis of cycling [10] and jumping [172]. A freely available open license motion analysis software package called Kinovea has been used in biomechanical research for applications ranging from sprinting to cliff jumping [85, 167, 171, 172]. Research shows a strong intra-class correlation (ICC), between the time splits measured using Kinovea and an infrared platform (OptoJump IR, Microgate, Italy) (ICC =1) [172]. Intra-tester reliability was reported to have a correlation outcome of ICC > 0.926 for a wrist flexion task when measured with markerless motion capture using Kinovea [93]. While valid and reliable analyses of a number of human movements have been carried out using Kinovea, no such assessment has been made for markerless motion capture of the BMX SX gate start. Once a valid and reliable method has been found, athlete movement characteristics can be correlated to kink time in order to characterise the optimal performance technique.

The aim of this research was to establish the validity and intra-tester reliability of a markerless motion capture approach using a high-speed (120 FPS 720 p) GoPro® Hero4 Silver camera and Kinovea for marker digitisation and angle generation during the BMX SX gate start. It was hypothesised that this method would be valid and reliable for measuring a range of movement and spatio-temporal kinematics.

7.4 Methods

7.4.1 Tester

The same tester was used throughout the study. The tester was experienced in the use of Kinovea for markerless movement analysis, having completed over 40 hours of markerless movement analysis with Kinovea before commencing the study. The tester was also experienced with marker-based motion capture in both 2D and 3D environments.

7.4.2 Participants

Participants were recruited by the BMXA HPU from BMXA HPU scholarship holders (*n* = 5) and BMXA Development Academy athletes (*n* = 5). All athletes had competed internationally for at least 5 years and were ranked by the Union Cycliste Internationale (UCI) and were a minimum of 16 years of age. Six male and four female athletes were selected. The average age of athletes at the time of data collection was 23.3 (± 2.2) years. Participants were instructed to wear normal competition clothing and protective wear. Bike setup details, including tyre brand and size, crank length and gearing, were recorded for each participant. Informed written consent was obtained from each participant in accordance with Bond University's Human Research Ethics Committee.

7.4.3 Equipment

GoPro® Hero 4 Silver (GoPro Inc., USA) cameras fitted with Class 10 Micro SD cards were used to collect video data at 120 FPS and 720 p on a 'normal' lens setting. These were fixed to the ramp platform with proprietary brackets. The brackets were permanently fixed to the platform and used for all data collection to ensure consistency between sessions. The brackets were set up to place the camera approximately in line with the centre of the bike's bottom bracket when in the start position on the ramp as per Figure 7-2 so that the rider was positioned in the centre third of the frame. Each file was time stamped and logged against kink time for the participant.

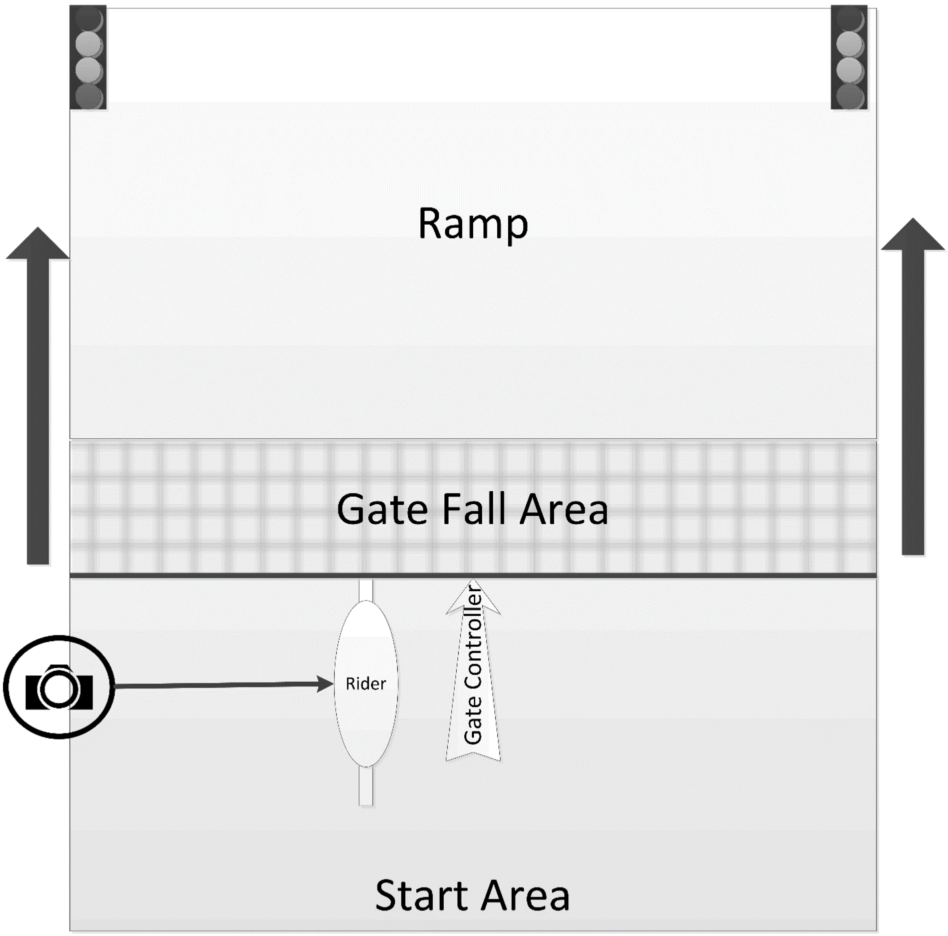

Figure 7-2 Top view of the ramp showing rider, gate and camera positioning. Not to scale.

Timing data was collected using a Mylaps AMB ChipX (Mylaps Sports Timing, The Netherlands) timing system. A decoder loop was permanently fixed at the ramp kink ensuring repeatability of measurement for the kink time split. MyLaps AMB Data Collector 3 Software (Mylaps Sports Timing, The Netherlands) was used to capture the data which was then exported into BEM (BMX Event Manager) Train (version 1.3.3), a bespoke BMX timing data logging program.

The video recording was considered to ‘start’ at the red light (first tone). The camera frame rate selection and camera position was defined by the fact that the rider typically begins moving between the first and second orange lights (second and third tones) (i.e.15-30 frames after the red light at 120 FPS). The camera position was set so that the initial rider and bike movement was centred in the centre third of the frame. The first crank was typically completed between 90 -110 frames and the second 140-150 for world class and elite athletes. The action from movement initiation to the base of the first crank was a full body action unique to BMX riding, the majority of which was observed in frames 50-100.

7.4.4 Data collection protocol

Video data was collected at BMXA HPU gate training sessions under the supervision of the BMXA HPU coaches at the Sleeman Sports Complex BMX SX track, Brisbane Australia with an Olympic standard SX ramp. During the session the coaches and athletes also used their own video equipment to obtain footage to provide augmented feedback to their athletes. After a warm up, each participant performed 10 individual maximum effort gate starts. Only one rider lined up for each start. The rider could select from any of the lanes to the left of the gate start mechanism as described in Figure 7-2 (i.e. lanes 5-8). The standard UCI BMX SX gate procedure was used. After descending the start ramp, the participants typically took the first 1-2 jumps and then tapered off, requiring a high intensity effort for less than 5 seconds per gate start. During the gate start training sessions, the focus was on producing the fastest possible time to the kink. Rest periods were self-selected and ranged between 3 to 15 minutes.

Participant information and timing data were exported to a spreadsheet after completion of each session. Video files were time stamped with a GPS date/time at the point of recording. The GPS date/time was used to match the video files to the timing data from the BEM system which logged each kink time split the GPS date/time of the trial. A summary of all complete trials was logged in a bespoke database that linked filenames to trials. Video files were considered to 'start' when the red start light turned on, and continued for 150 frames from that point which represented the gate start action to at least the base of the second crank for all participants. The fastest trial for each participant was selected for use. A total of 10 trials (one trial for each of 10 participants, each of 150 frames) were used for analysis.

7.4.5 Validity study methods

The ideal validity study would compare the outputs of the novel method to those from a 3D motion capture system, the current Gold Standard. Fonda et al [57] (*n* = 11) measured the validity of a 2D video system against the Gold Standard 3D system for cycling on an ergometer in a laboratory. An average difference between 2D and 3D measures of 2.2° was reported for the knee angle, while Umberger et al [176] (*n* = 4) showed a difference in maximum knee angle of 2.2 ° and minimum knee angle of 2.3°. However, data capture using a 3D motion capture system in this environment was not feasible for several reasons. The first problem was the inability to attach markers to the athletes. As explained previously, the athletes wear loose fitting clothing over safety equipment. Therefore, we were unable to attach markers to their loose fitting clothing as the movement of the applied marker relative to the joint would have been unacceptable. It was also not possible to securely attach the markers to the relevant anatomical landmarks due to the safety equipment worn on many joints underneath the baggy clothing and due to the fact that securely attaching markers to the body would negatively influence the BMX riders feel of the movement, thus reducing the ecological validity of our assessment. The second reason related to appropriate camera placement. The ramp has a very steep gradient (15 - 28°). To gain a 3-D perspective of the gate start motion, it would require placing a number of cameras on this slope. The surface of this slope cannot be altered with any tape, bolts, etc. that may leave a residue, damage the BMX wheels or increase the risk of injury to the athlete. The surface is quite slippery which makes it difficult to place a camera mount in front of the rider in a stable position. Thirdly, when the gate drops, the entire platform shakes. For 2D cameras tracing makers, the relative positioning of the markers in the 2D image remains the same so this does not create a problem. For the 3D system, this would require recalibration after the gate drop. This is problematic as the gate drop occurs part way through the action – thus the cameras would have to be recalibrated half way through the action each time, which is impossible as the action cannot be paused. The alternative was to use the novel methodology to measure a known angle that is consistently able to be seen throughout the motion as used in previous studies [89, 177, 178].

To determine the validity of the calculations, the angle between the bicycle seat stay and the chain stay was measured with a goniometer. All the other angles of the bike were obscured by the rider at some point. This measurement was taken in a stable environment 3 times while the bike was stationary as per Figure 7-3. The average of these three measurements was calculated. This was validated against the manufacturer’s specifications. This was completed for one single bike.

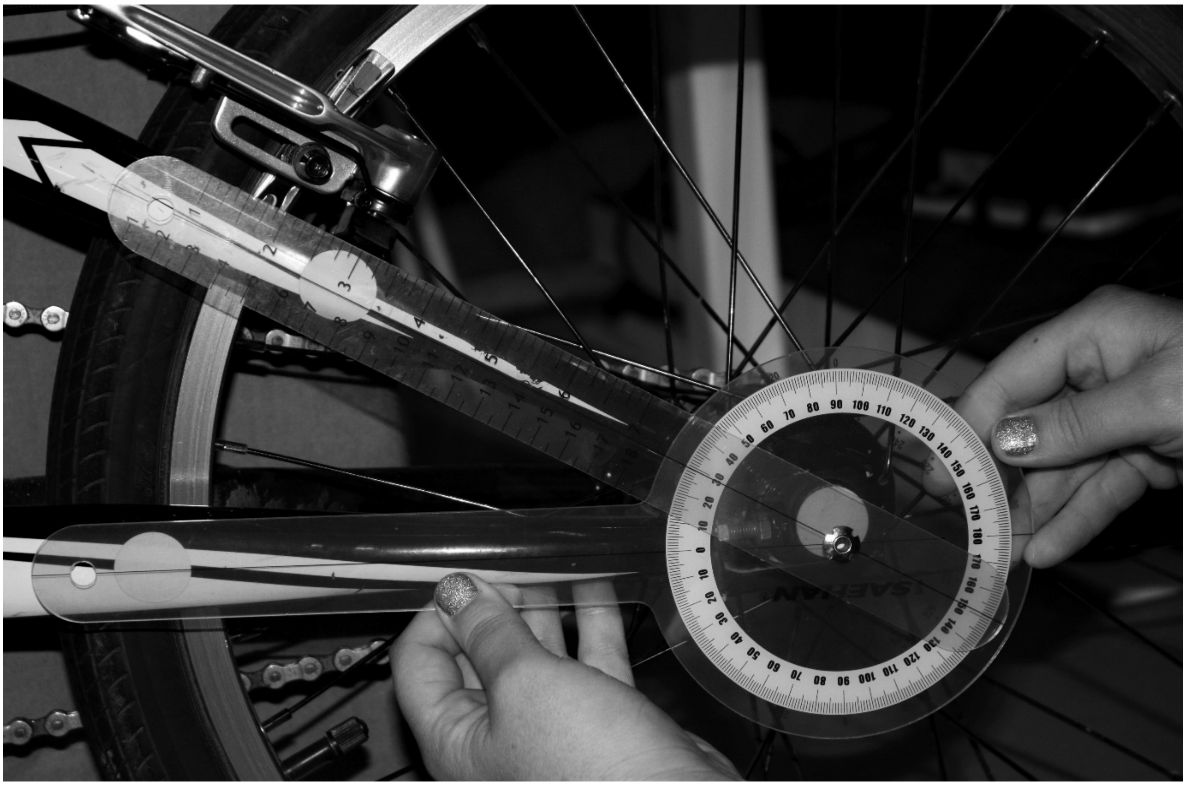

Figure 7-3 The angle between the seat stay and chain stay with the axis at the rear wheel hub was measured with a goniometer with the bike in a stable position. The stationary and movement arms of the goniometer were set so that they were aligned with the centre

A World Class rider performed a maximum effort gate start on the Sleeman Sports Complex BMX SX track on the measured bike. The footage was imported into Kinovea. The version currently presented by the developers of Kinovea as stable is 0.8.15. An experimental version that offers more features is also available (0.8.25), however the researchers did not find it as stable as version 0.8.15. Virtual points were identified on the chain stay, seat stay and at the rear wheel hub corresponding with the angle measured with the goniometer.

The coordinates of these points at frame 1 were recorded. The trajectory of these points was tracked for the first 150 frames taken from the red light. The angle defined by these three points was calculated in Matlab for each frame (150 frames) and compared to the average goniometer measure to determine whether the markerless motion capture methodology is valid and if this validity may be affected by any degree of parallax error that may occur more so at the extremities of the field of view.

7.4.6 Intra-tester reliability study method

For each trial, virtual markers were added to the participant at the elbow, shoulder, hip, knee, ankle and toe in Kinovea (version 0.8.15) as shown in Figure 7-4 to define the angles shown in Figure 7-5. Virtual markers were also added to the end of the handlebar, front of the helmet and rear of the helmet. To track the crank angle, the centre of the crank and a point along the arm of the crank were marked. Where the angle was calculated to the vertical the orientation of the image was checked using the grid function in Kinovea to match the global image vertical to vertical objects such as vertical fixings and hung objects that acted as plumb lines. The coordinates for each marker at the first frame were recorded in the database. The trajectory of each of the 12 markers was tracked through 150 frames. The trajectories were labelled and exported as .xlm files.

Figure 7-4 Virtual markers are added to the figure and tracked through 150 frames. Markers are added to the front of the helmet, rear of the helmet, front hub, handlebar end, elbow, shoulder, hip, knee, ankle, toe, crank centre and crank end.

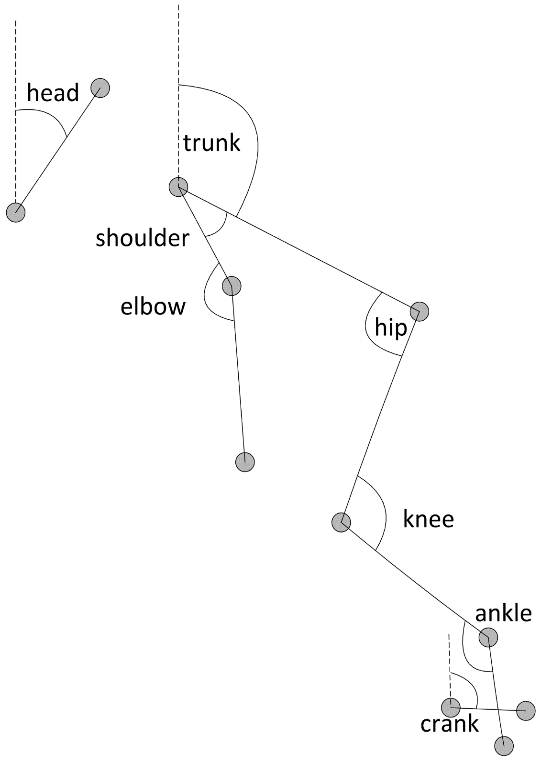

Figure 7-5 Body segments are created by connecting the markers. Joint angles are created from the angles between these virtual segments

To quantify the intra-tester reliability of this markerless motion capture method, this digitisation process was repeated by the same tester for the 10 trials. The average time between the re-analysis of the 10 trials was 54.8 ± 30.8 days (range: 28-106 days).

7.4.7 Data analysis

The workflow for data analysis and statistics is described in Figure 7-6.

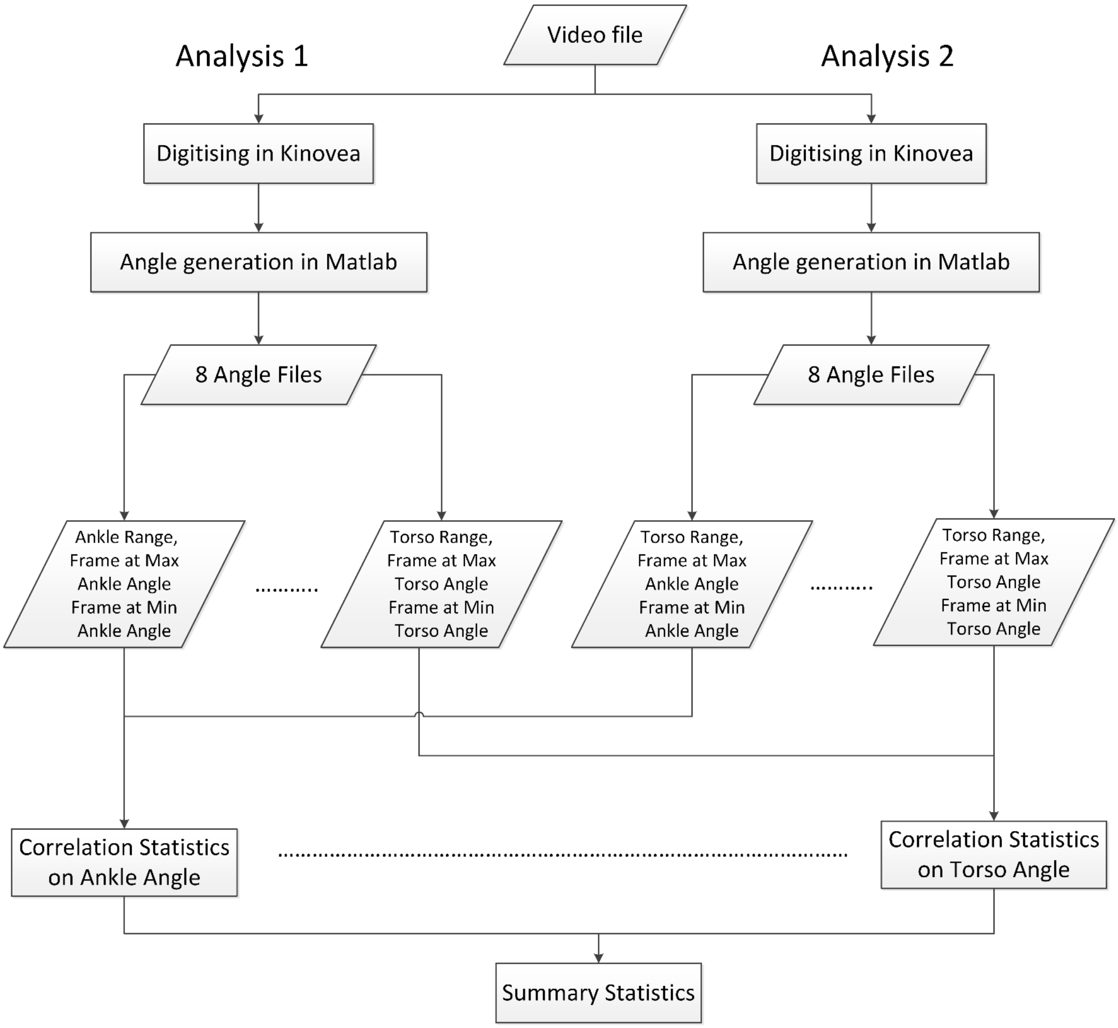

Figure 7-6 Data analysis work flow for intra-tester reliability study.

The .xlm files generated by each analysis in Kinovea were imported into Matlab® R2014a (The Mathworks Inc., Boston, MA, USA). For both the validity and reliability studies, the trajectories were converted from local coordinate systems, to global, by translating using the initial coordinates in frame 1 that are already in the global system (x_1, y_1) and the local coordinates (x_i , y_i) for the frames from 2-150 as per Equation 1.

Equation 1.

$$For\ i = 2 - 150\ where\ x_1\ is\ the\ marker\ location\ on\ the\ first\ frame$$

$$x_i = x_i + x_1$$

$$y_i = y_i + y_1$$

Ankle, knee, hip, shoulder and elbow angles were generated in Matlab by considering the vectors between marker coordinates as body segments as shown in Figure 7-5. The head, torso and crank angles were all measured relative to the vertical. All angles were generated for each of the 150 frames per trial.

The angles were generated using trigonometry calculations as described in Equation 2.

Equation 2.

$[\mathbf{DistalSegment}] = (\mathit{DistalMarker})\text{-}(\mathit{JointMarker})$

$[\mathbf{ProximalSegment}] = (\mathit{ProximalMarker})\text{-}(\mathit{JointMarker})$

$$CosTheta = \frac{dot[\mathbf{DistalSegment}, \mathbf{ProximalSegment}]}{(norm([\mathbf{DistalSegment}]) \times norm([\mathbf{ProximalSegment}]))}$$

$$JointAngle = \frac{\cos^{-1}(CosTheta) \times 180}{\pi}$$

The angles were written to variables on which statistical analyses were performed.

Each analysis generated 8 angle measurements across 150 frames. The maximum and minimum of each angle were recorded and written to file, as were the frames at which these occurred. The frame at which the maximum and minimum angles occurred represented a spatio-temporal measure for the movement.

7.5 Statistical analysis

7.5.1 Validity study statistical analysis

For the validity study the angle calculated for each of the 150 frames in the trial was compared to the measured angle, which was considered the ‘true’ angle as the goniometer measurement agreed with the manufacturer’s specifications. The average absolute error was calculated. The statistical power was then calculated with the DSS Research Knowledge Centre Toolkit, with a two tailed test and Alpha set at 5% [179].

7.5.2 Intra-tester reliability statistical analysis

To ascertain if the reliability was different for each athlete, each trial was considered separately and the results analysed. To ascertain if the reliability was different for each joint, each joint was also considered separately and the results analysed. The absolute difference between angles generated by the two analyses was calculated in Microsoft Excel (version 2015, Microsoft Corporation, Seattle, WA). This was averaged for each trial (i.e. for each athlete) across the 150 frames, then the average for each trial was averaged and tabulated. Similarly, the average absolute error (AE) and coefficient of determination (R^2) were calculated in Excel and the intra-class correlation (ICC, one-way random) was calculated in IBM SPSS Statistics (version 23, IBM, Armonk, NY) comparing the first and second analysis of each trial (one per rider i.e. $n = 10$) across the eight angles. The results for each trial were averaged to create an overall average for each joint and tabulated. The discrepancy in a spatio-temporal measure between the two analyses per trial was represented by the difference in the frame number at which the maximum and minimum angles occurred. The AE, R^2 and ICC were reported for all spatio-temporal measures. The statistical power was then calculated with the DSS Research Knowledge Centre Toolkit, with a two tailed test and Alpha set at 5% [179].

7.6 Results

7.6.1 Validity study results

The validation results gave a standard error of 1.56 ± 0.92°. This value varies as shown in Table 7-1 with the highest error range being in the mid-section where the range of movement was greatest. The statistical power was calculated to be 100% for α = 0.05 and the sample size of 150 which was considered acceptable.

Table 7-1 Validity study results: average absolute error (AAE) results (°). The average difference between the measured angle and the 'real' angle for frames 0-150, 0 - 50, 51 – 100 and 101 - 150.

Overall AAE° (*SD*)	Frames 0-50 AAE° (*SD*)	Frames 51-100 AAE° (*SD*)	Frames 101-150 AAE° (*SD*)
1.56 (0.92)	1.41 (0.75)	1.90 (1.12)	1.33 (0.73)

7.6.2 Reliability results

Figure 7-7 shows the angle v. time for the eight angles of interest for a typical trial.

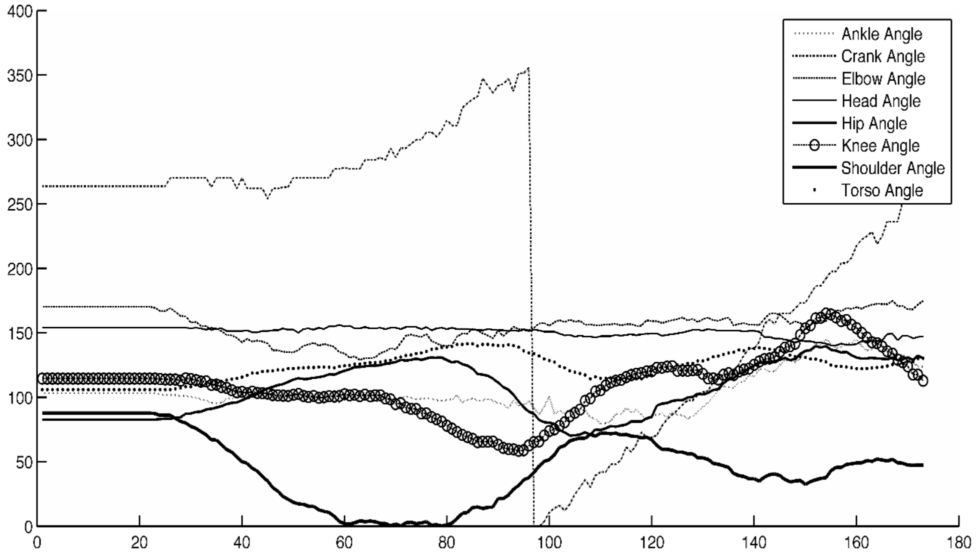

Figure 7-7 Angle vs time for eight kinematic measures for a single trial.

The data in Table 7-2 is the average of the values calculated for each trial (i.e. athlete) for each joint. The average absolute error (AE) ± standard deviation (SD) for each participant was calculated for each measured angle. The average of these values was calculated for each angle as displayed in Table 2 (column 1). The largest average AE for the joint and segment angles was 5.7 ± 3.1° (elbow angle) and the smallest was 4.2 ± 3.2° (head), and the average AE over the entire system was 4.8 ± 0.5°. The R^2 and ICC showed strong positive correlations averaging 0.93 ± 0.10 and 0.92 ± 0.06 respectively across the whole system. The average AE of the measured range of motion at each angle across the 10 participants was highest (8.2 ± 5.3°) at the elbow (representing 18.6% of the average range of motion at the elbow) and the lowest was 3.0 ± 2.9° at the ankle (representing 5.0% of the average range of motion at the ankle) (column 4). The R^2 and ICC showed strong positive correlation averaging 0.73 ± 0.14 and 0.80 ± 0.10 respectively across the whole system.

For each trial the frame at which the maximum and minimum angle occurred was recorded. The difference in the frame at which the maximum/minimum angle occurred between the two analyses was calculated for each athlete and called the AE of this measure. The average AE was calculated across the ten athletes for each joint as is shown in Table 7-2 column 11 for frame maximum angle and 15 for frame minimum angle. The greatest average AE for the maximum angle temporal measurement was 6.7 ± 8.1 frames (head). This represents 0.06 ± 0.07 s. The average across all joints was 3.4 ± 2.4 frames which is 0.03 ± 0.02 s. The greatest average AE for the minimum angle temporal measurement was 8.1 ± 10.3 frames (shoulder). This represents 0.07 ± 0.09 s. The average across all joints was 3.9 ± 3.3 frames which is 0.03 ± 0.03 s.

The average correlation statistics for the frame at which both the maximum and minimum angles occurred were $0.81 \pm 0.29 < R^2 < 0.97 \pm 0.02$ and $0.90 \pm 0.19 < \text{ICC} < 0.98 \pm 0.01$ across the eight angles with the minimum angle having a lower correlation than the maximum angle.

For the absolute error of the measurement and the range of motion the statistical power was 100% throughout. This was reduced for the temporal measures with the lowest being for the minimum head angle which was 36.1% and the highest being for the Maximum angle of the shoulder which was 100%.

*Table 7-2 Reliability results summary table. AE = Average absolute error. R^2 = Average coefficient of determination. ICC = average intra-class correlation (one-way random). Range = average range of motion measures. Frame Max Angle = the frame at which the maximum angle was measured. Frame Min Angle = the frame number at which the minimum angle was measured. n/a = Not applicable. SD standard deviation * For the crank the maximum angle is taken as 180°. **For the crank the minimum angle is taken as 0°.*

	AE (°) (SD)	**R^2 (SD)**	**ICC (SD)**	**AE Statistical Power**	**Ave Range of Motion (°) (SD)**	**AE Range of Motion (°) (SD)**	**R^2 Range of Motion**	**ICC Range of Motion**	**Range of Motion Statistical Power**	**AE Frame Max Angle (frame) (SD)**	**R^2 Frame Max Angle**	**ICC Frame Max Angle**	**Frame Max Angle Statistical Power**	**AE Frame Min Angle (frame) (SD)**	**R^2 Frame Min Angle**	**ICC Frame Min Angle**	**Frame Min Angle Statistical Power**
Ankle	5.1 (1.4)	0.89 (0.08)	0.90 (0.11)	100	59.7 (10.1)	3.0 (2.9)	0.86	0.92	90.5	4.3 (4.9)	0.97	0.99	79.2	2.1 (2.3)	1.0	1.0	82.3
Crank	4.7 (1.4)	0.97 (0.04)	0.99 (0.01)	100	360 (0.0)	n/a	n/a	n/a		2.0 (1.6)*	0.97*	0.98*	97.7	1.4 (1.8)**	0.98**	0.98**	69.1
Elbow	5.7 (3.1)	0.85 (0.14)	0.89 (0.14)	100	44.2 (14.3)	8.2 (5.3)	0.84	0.75	99.8	5.8 (9.5)	0.97	0.98	48.8	8.1 (8.9)	0.53	0.92	82.1
Head	4.2 (3.2)	0.89 (0.03)	0.82 (0.18)	100	23.8 (6.5)	3.2 (3.9)	0.71	0.73	73.7	6.7 (8.1)	0.92	0.97	74..4	7.1 (14.0)	0.92	0.96	36.1
Hip	4.3 (1.7)	0.96 (0.02)	0.95 (0.04)	100	63.8 (9.1)	5.7 (5.1)	0.58	0.68	94.2	3.8 (6.0)	0.97	0.98	51.7	0.8 (1.3)	1.00	1.00	49.4
Knee	5.0 (4.7)	0.98 (0.01)	0.93 (0.13)	100	91.3 (13.6)	3.4 (2.5)	0.90	0.96	99	0.4 (0.5)	1.00	0.98	71.6	1.6 (1.2)	0.98	0.99	98.9
Shoulder	4.8 (1.8)	0.98 (0.02)	0.94 (0.09)	100	84.4 (8.8)	5.0 (3.2)	0.63	0.79	99.9	0.0 (0.0)	1.00	1.00	100	8.1 (10.3)	0.23	0.43	72.2
Torso	4.3 (3.4)	0.95 (0.02)	0.94 (0.21)	100	36.3 (5.3)	3.4 (2.1)	0.59	0.74	99.9	3.9 (2.6)	0.95	0.97	99.7	1.6 (2.1)	0.94	0.95	98.8
Average	4.8 (0.5)	0.93 (0.10)			n/a	4.6 (1.8)	0.73 (0.14)	0.80(0.10)		3.4 (2.4)	0.97 (0.02)	0.98 (0.01)		3.9 (3.3)	0.81 (0.29)	0.90 (0.19)	

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

7.7 Discussion and implications

Kinematics is useful for describing movement, however more than one parameter needs to be recorded to build a meaningful and useful description of the movement. Traditionally, kinematics have been measured under laboratory conditions. As research has shown that there can be a significant difference between field and laboratory based results [54, 86], valid and reliable field based methods are necessary to gain an understanding of movement occurring in field environments [54]. A valid and reliable method of measuring performance characteristics during BMX gate start training is required to define key movement characteristics affecting performance outcome, and to identify movement maturation. With evidence based research, coaches can then provide quantitative knowledge of performance feedback. On this basis, the aim of this research was to establish the validity and intra-tester reliability of a markerless motion capture approach using high-speed cameras and Kinovea for marker digitisation and angle generation during the BMX SX gate start.

The absolute error of the validity assessment was 1.56 ± 0.92° across the 150 frames. In order to ascertain the segment in which the measurement was least reliable the validity results were broken down to the first 0-50 frames; where the rider is preparing for the green light and movement is minimal, then 50-100 frames; where the initial power action is activated and the movement pattern is at its fastest, and then 100-150 frames; where the bike moves from the central third of the frame to the outer third. This last 50 frames are where the magnitude of parallax error and the impact of distortion due to the nature of the action camera lens is likely to be at its greatest. The error was greatest in frames 50-100 (1.90 ± 1.12°) and decreased in the final 100-150 frames to 1.33 ± 0.33° which suggests that the impact of the lens distortion at the periphery and parallax issues are minimal with this setup. The average remained under 2° which was considered acceptable in this context and when compared to the literature [88, 89, 180, 181].

For example, the validity of the Microsoft Kinect® markerless motion capture system for capturing the position of static jig was determined by comparison to a 3D retro reflective motion capture system [88]. The angle measurements from both the Kinect and 3D systems agreed within < 0.5° in sagittal and frontal planes with a coefficient of reliability of < 0.5° [88, 89]. Fonda et al. (2014) measured the knee angle of 11 cyclists through 15 cycles on an ergometer in a laboratory. Kinovea 0.8.15 was used for the 2D analysis. There was no significant difference between 2D and 3D measures of the knee angle at bottom dead centre (2D 42.1 ± 7.4º; 3D 42.9 ± 8.5º for trial 1 and 2D 43.8 ± 7.5º; 3D 43.9 ± 6.7º for trial 2). It was found that seat height made a difference to the validity, with the higher seat height resulting in a difference of 2º. A further study would be to repeat this with a standing position as per the BMX pose. The results of Fonda et al. (2014) for knee angle compared favourably with those from Umberger et al [176]. Umberger et al [176] also compared 2D and 3D lower body kinematics ($n = 4$) of cyclists on an ergometer in a laboratory. The results showed that the hip showed the largest discrepancy. Some of this was due to different models being used for the hip angle calculation where the 2D model used the knee-hip-shoulder apex and the 3D model used the femur-hip-pelvis apex. The cross correlation coefficients for the sagittal hip, knee and ankle angles were 0.97, 0.98 and 0.98 respectively.

Castelli et al. (2015) compared gait characteristics of the hip, knee and ankle joints at slow, comfortable and fast speeds using a markerless system with the gold standard marker measurement method. Across all speeds, the highest R^2 was at the knee (0.99). The fast speed showed the lowest coefficient of determination at the ankle ($R^2 = 0.82$), knee ($R^2 = 0.98$) and hip ($R^2 = 0.96$). The average root mean squared deviation between the joint kinematic curves produced by each method also showed a greater deviation at higher speeds (4.7º at the ankle, 4.1º at the knee and 6.1º at the hip) [180].

In addition to demonstrating the validity of the markerless motion capture method, reliability also needed to be shown before it could be considered for use in the field.

The intra-tester ICC values found in the present study reflected high to near perfect correlations [137]. The average AE remained under 6° for all measures, with the smallest being the head and the largest being the elbow with a statistical power of 100% for all measures. The elbow had a lower correlation value which reflected the difficulty in identifying the joint centre in athletes with greater shoulder abduction.

The correlations for the elbow data tended to be higher in the World Class participants than the Elite participants (R^2 = 0.87 vs 0.76) and were higher in males than females (R^2 = 0.89 vs 0.78). These potential differences between participants of different standards and genders could reflect a difference in technique or strength between the World Class and Elite, and males and females that alters the ease of markerless BMX motion capture. A similar effect was noticed relating to leg rotation at the hip by Umberger et al [176] where 2d knee angle measurement was compromised by athletes who tended to externally rotate at the hip at the top of the pedalling cycle. This warrants further research.

In a similar study, Bowerman, Whatman, Harris and Bradshaw (2013) performed an intra-tester reliability study to measure the reliability of measuring the pelvic and knee angles from a markerless motion capture image in Kinovea. In measuring the extremity alignment in nine elite adolescent ballet dancers performing a fondu, an intra-tester error (determined with two days between test and retest) of 1-2° for knee and pelvic angle measurement was found [90]. Similarly, Abd-El Raheem et al. (2015) reported an intra-tester reliability ICC ≥ 0.926 using Kinovea to measure wrist movement in a simple wrist action, with no AE reported. A two day period was observed between test and re-test [93]. Although these studies [90, 93] were performed in laboratory conditions and utilised shorter periods of time between assessments of the same video files, it appears that the current study achieved relatively similar levels of intra-tester reliability in a much more dynamic and challenging environment.

Insight into the temporal reliability of the markerless motion capture method was obtained by quantifying the frame at which maximum angles occurred. The most reliable was the knee which was near perfect across all measures and the least the shoulder for which the frame corresponding to the minimum angle showed the lowest correlation of all (R^2 = 0.23, ICC = 0.43). This may be due to the difficulty in reliably identifying elbow joint centres in dark uni-coloured clothing during a period of rapid movement. The overall high intra-tester correlation for each of these timings was considered adequate for this purpose [137]. The statistical power of these measures was less than for the angular measures and the ranges of motion.

Within the present study, the tester reported a significant learning effect during the pilot testing conducted before commencing this study, and still felt some learning occurred during the study. The question this poses is whether further practice could result in additional improvements in intra-tester reliability. Noticeable factors that affected the tracking of virtual markers in Kinovea included the colour of the clothing worn by the participant, transition from shade to sun as the rider came out of the cover of the ramp platform roof on a sunny day, extreme humidity which affected general visibility and the contrasting colour of the crank, bike, shoes and socks.
As each trial produced one range of motion per joint, one minimum angle and one maximum angle, there were effectively ten values from which to gather statistical power. The range of motion calculations all exhibited a high statistical power with the lowest being at the head. For most participants the head has a very small range of motion (average of 23.8 ± 6.5º) which had an intra-tester reliability ICC of 0.73. Increasing the sample size to 20 could significantly improve the power of the study for the motion of the head, but may not impact the reliability. As the helmet is a solid object it may be possible to attach stickers that contrast to the base colours of the helmet to act as markers for further research into head movement.

The larger standard deviations in the AE for the Frame Max Angle for the elbow, head and hip caused a lower statistical power. Again, adding further trials to the study could increase the statistical power but may not reduce the absolute error. It was noted that the large standard deviations were caused by particular outliers. These outliers corresponded to issues such as uni-coloured clothing as discussed previously.

It is important to note that the study is restricted to a limited capture space. The maximum distance travelled by the athlete and bike through the 150 frames was 3.1 m in the horizontal plane and 1.2 m in the vertical plane. This took the athlete and rider to the edge of the frame. This limitation is noted as beyond the centre third capture area errors of parallax need to be considered. The GoPro Hero 4 Silver camera is an action camera and if used on the wide setting the effect of the fisheye lens distorts the image. Whilst Kinovea 0.8.25 onwards offers a distortion correction this is a multistep process involving photographing a screen display of a specified grid, then overlaying the distortion grid on this image. The distortion grid is then used to calibrate for camera distortion. Inaccuracies can enter this process if the screen itself has a curvature, and then at the point where the user overlays the distortion grid on the image. GoPro Studio 2.5.9.4139 (GoPro Inc., USA) has an inbuilt function that corrects the image for the fisheye. This uses a mathematical algorithm based on the curvature of the lens specifications that alters the image. As this algorithm is specifically designed to fit this particular model lens with no intervention required by the user, it is more likely to produce a truer result than using the multi-step Kinovea distortion correction function. In support of this view the validity results reported in this manuscript indicate that any distortion due to lens curvature is not a significant concern, with the degree of inaccuracy not exceeding 2°. The advantage of using a commonly accessible action camera, despite the fisheye lens, is that they are readily accessible and affordable for the purposes of research and coaching. As the target audience of further research is coaches, it was deemed important to use a methodology that was easily reproducible by coaches in the field.

7.8 Conclusion

Markerless motion capture is an ecologically viable method for measuring real-world performance, in this case rider kinematics on a BMX SX start ramp. This study demonstrates that markerless motion capture can be valid to within 2° with a high intra-tester reliability. As such it is a suitable method to use to conduct further research into the rider kinematics of the BMX SX gate start action. As these results were obtained with a relatively experienced Kinovea user, such results may not necessarily apply to someone with less experience. In addition to further practice by the Kinovea user, additional improvements in the reliability of this process may be obtained by requesting the participants wear contrasting clothing, ensure sufficient lighting, and adding tape to clothing at joints such as the elbow. There is much yet to be learnt about the kinematics of the BMX gate start and the method of markerless motion capture used in this study provides a valid and reliable tool for further research.

Chapter 8: Study 5 Kinematic analysis to describe a ‘fast’ BMX SX gate start

8. Study 5 Kinematic analysis to describe a ‘fast’ BMX SX gate start

8.1 Preface

The aim of this study was to describe a ‘fast’ gate start action. Studies 2 and 3 highlighted the importance of the entry into the second crank, which helped to direct the focus of this study into the kinematics of the first three cranks to specifically focus on the positioning of the body into the second crank. A large number of kinematic parameters were collected for this study and different methods were used for analysis from statistical analysis to qualitative based categorisation. All analyses were directed towards investigating and profiling the characteristics of the fastest starts as defined by the kink time split (i.e. the time split taken at the change in gradient of the ramp at ~ 3m). Data from the fastest starts were then contrasted with data from the slowest starts facilitate identification of key kinematic differences between fast and slow start actions. The different formats of data collected enabled varying ways of describing a ‘fast start’ which were tied together in the discussion in a translation for coaches. The various data analysis methodologies all revealed commonalities in technique that appear to be significant characteristics of a movement pattern that creates a ‘fast’ gate start.

8.2 Abstract

Coaching staff from Cycling Australia are already applying the findings of this study to improve the gate start performance of Elite and World Class athletes. The results have been presented at coaches' meetings and were well received by both athletes and coaches, with athletes keen to understand and improve their own gate start actionThe aim of this observational study was to describe a 'fast' BMX SX gate start action using kinematic analysis. Fourteen World Class and Elite athletes each performed five maximum effort gate starts as part of a regular training session on an 8 m SX gate using the standard gate start protocol. The action was recorded on the left (non-lead leg side) with GoPro Hero action cameras at 120 fps and analysed with Kinovea to measure five joint and two segment angles across the first 1.2 s of the action. A moderate to strong correlation was found between the recoil (i.e. rearward movement) of the rear and front hubs of the bike, and performance. The front hub trajectory was traced throughout the movement to identify specific characteristics related to performance. Three types of hub trajectory were identified, with the *hairpin* being used by the fastest athletes. Three types of set position, *back*, *upright* and *angled*, were identified according to common joint angles, specifically at the non-lead knee and shoulder. The *back* set position was most likely to result in the *hairpin* trajectory, which facilitated the most efficient transfer of the centre of mass and generation of forward propulsive force through the gate start action. Coaches and athletes can use this information as a basis underlying skill acquisition and/or strength and conditioning approaches to better prepare developing athletes for competition at a higher level.

8.3 Introduction

The gate start is a critical component of the BMX SX race and as such is a major focus in training [127, 153]. Various theories have been put forward by coaches about the ideal gate start, however there is very little peer-reviewed data to support these theories. Common cues such as 'drive the hips forward', 'handlebars to hips', and 'up and over' [182] are starting to be expanded and even challenged [183] as the depth and breadth of knowledge grows and information is more readily shared via the internet. Gate start training often focuses on the initial action from the set position to the point at which the front hub passes the kink in the ramp ~ 3 m from the start[14]. The kink time split is often used in training as a performance outcome in gate start training. At the kink the athletes aim to have at least a handle bar (~ 10 cm) advantage over other athletes [127] giving them a tactical advantage into the first jump and previous research has shown that the athlete who lands this jump first is most likely to win the race [5, 127].

The BMX gate start action is a complex gross motor action. Preliminary studies have been done to describe the movement characteristics of the action in 2D and 3D [16, 38, 45, 127-129][15]. There is now a need for more comprehensive research involving a greater number of participants, a validated and reliable kinematic measurement methodology, and expert participants to better understand the key kinematic movement characteristics that describe a 'fast' gate [127]. Research has shown that kinematics can provide a basis for knowledge of performance feedback that can result in an improvement in performance outcome [184, 185]. Schmidt et al [184] describe augmented kinematic feedback as:

> *"extrinsic, postresponse, usually verbalizable information about some aspect of the movement-pattern kinematics. Such information refers to aspects of position, velocity, or acceleration of the limbs, frequently as a function of time, and also may include information about the actions of the limbs with respect to each other (i.e. coordination)" p. 14-15.*

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[14] See Figure 1-1 for a description of the ramp measurements.

[15] These studies are discussed in detail in §2.1

In order to use kinematics as a source of knowledge of performance, there must be an understanding of what kinematic movement characteristics are related to optimal performance. This was explored by Schmidt et al [184] where the movement resulting in optimal performance outcome was described as the ‘goal pattern’.

In the study by Schmidt et al [184] kinematic feedback was used to improve performance in a batting simulation study. In order to identify the ‘goal pattern’ for a simple batting simulation task, where the aim was to hit a virtual ball (represented by a light series) with a bat, 10 subjects performed 100 trials with knowledge of results (i.e. success of intercept of virtual ball and bat) given after each trial. Two retention tests (20 trials each) were performed, one 10 minutes after the test, and the next a day after the test [184]. The position, velocity and acceleration of the bat in the task were recorded and the patterning of the most proficient participants was reported and used as the ‘goal pattern’. For position, velocity and acceleration, there were high within-subject correlations and low within-subject variation for those deemed as proficient. In a second experiment within the same study, key features of the goal pattern were added to the training program for a second test of 12 subjects each of whom practiced for nine days. The researchers used the goal pattern descriptors to try and predict the most proficient performers. Two temporal variables were found to be effective predictors of performance; one being the time at which the participants began the second part of the movement ($r = -0.86$), and the other being the start of acceleration toward the target ($r = -0.90$). Again, for the more proficient participants within subject variability was lower than that of the less proficient participants. The experiment reported in Schmidt et al [184] showed that by using simple kinematics predictors of success can be determined by observing the action of a proficient group, and then used to train a second group to help achieve proficiency and to predict performance.

Analysis of performance should be based on a selection of performance indicators. In Zabala, Sanchez-Munoz and Mateo [14], it was suggested that the most common areas of weakness during a gate start were the lack of the following factors: forward movement in the trunk, getting the front wheel to ground in a timely manner after negotiating the fall of the gate, anticipation of the start and continuation into a strong pedalling action after the first crank, however no evidence was presented to substantiate this theory. Although prefatory studies have been done in BMX gate start kinematics [16, 38, 45], there are no known gate studies of high scientific rigour [127]. Previous studies have been limited by the number of participants and trials, with the number of athletes and analysed trials per study being three athletes with one trial each, two athletes and one trial each and 12 athletes and one trial each respectively [16, 38, 45].

As discussed by Schmidt et al [184] with the batting simulation experiment, the timing of events can be an important predictor of performance. Marshall et al [186] described the concept of a ‘grand plan’ for complex gross movements such as a gate start, tennis serve or ball kick. In striking skills such as serving and kicking, research suggests a proximal to distal order of segment sequencing is necessary to maximise performance [186, 187]. This means that the movement is initiated at the larger, slower, and heavier segments at the trunk and as the speed increases movement is transferred to the next (more distal) segment. In kicking etc. the distal segment needs to generate maximum velocity, and the Summation of Speed Principle proposed in Bunn [188] suggested that speed of the distal end of a segment is a sum of the speeds of all segments proximal to that point. This is complicated in the case of BMX pedal stroke as the distal end of the shank segment is constrained by the pedal, and the distal end of the lower arm is constrained by the grip on the handlebar. As such the order of movement cannot be assumed based on previous research. Findings presented by this study may help coaches to understand the order in which segments need to be moved in order to replicate an optimal hub trajectory and therefore performance outcome.

This study aims to describe a ‘fast’ BMX gate start as performed by 14 BMX athletes using the following kinematic parameters:

a) Joint range of motion during the first 1.2 s,
b) The timing of maximum/minimum joint angles,
c) Relationship between results in a and b to kink time,

d) Range of values for rear recoil, hub recoil and hub height,
e) Relationship between results in d to kink time,
f) Kinematic description of the set position,
g) Identification of common ‘styles’ of set position,
h) Identification of common ‘shapes’ of hub trajectory through the movement and
i) Relationship of g and h to kink time.

8.4 Methods

In the study presented in this chapter, kinematic measures were used to determine performance characteristics of a group of expert BMX athletes with considerable gate start experience. Joint and segment angles were measured throughout the gate start action (first 1.2 s from start stimulus). These measurements were correlated to kink time to investigate the possibility of performance predictive factors. Temporal events such as reaching the edge of the gate and distances such as maximum height travelled by the front hub and recoil of the rear hub, were postulated as predictors of performance by the CA BMX HPU coach and called the Coaches’ Parameters.

A valid and reliable method was used to obtain joint and segment angles and the time points at which they occur in BMX gate starts and has been described in Grigg et al [129][16]. The variables measured were analysed quantitatively using statistical analysis and qualitatively using heat maps to identify patterns relating to performance. Hub trajectories and set positions were also examined qualitatively to identify patterns within, and between, participants.

8.4.1 Participants

All participants were WC[17] (*n* = 6; 3 female, 3 male) or Elite[18] athletes (*n* = 8; 1 female, 7 male), with an average age of 21.0 ± 2.8 years at the time of data collection. All athletes had a right leg lead and were uninjured at the time of

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[16] Reprinted as Study 4
[17] UCI SX race podium during the year of testing
[18] With a UCI ranking in the top 100 at the time of testing.

testing. To ensure safety, participants used their normal safety equipment and attire. Written informed consent was obtained from each participant in accordance with Bond University's Human Research Ethics Committee.

8.4.2 Data collection

All data were collected during training camps at the Sleeman Sports Complex BMX SX track, Brisbane, Australia with an Olympic standard SX ramp as described with the camera setup as per Grigg et al [129][19][20]. Each participant performed at least five maximum effort gate starts using a standard UCI BMX SX gate procedure. At the base of the ramp the participants typically took the first 1-2 jumps and then tapered off. Rest periods were self-selected and lasted 3-15 minutes as recommended in Phillips et al [149]. The trials were filmed from the athlete's left side, i.e. the non-lead leg with GoPro® Hero 4 Silver (GoPro Inc., USA) cameras fitted with Class 10 Micro SD cards at 120 FPS, 720 p on a 'normal' lens setting. Cameras were fixed to the ramp platform with proprietary brackets in-line with the centre of the bike's bottom bracket when in the race start position. The time of recording was used to match the video with the timing data which was collected using a Mylaps AMB ChipX (Mylaps Sports Timing, The Netherlands) timing system. A decoder loop is permanently fixed to the kink on the Sleeman SC ramp. MyLaps AMB Data Collector 3 Software (Mylaps Sports Timing, The Netherlands) was used to capture the data which was then exported into BEM (BMX Event Manager) Train (version 1.3.3). The footage of each trial was trimmed to 'start' at the red light (first tone) and finished at the 150th frame.

8.4.3 Data analysis

8.4.3.1 Kinematics

The parameters selected for measurement in this project reflected the collaboration of coach and scientist. A range of joint and segment kinematic parameters that have been commonly used in other forms of cycling were selected [10]. In addition, head angle was added as it was believed by the CA

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[19] Reprinted as Study 4

[20] See Chapter 3 for more details on the training camp format.

BMX coach that lifting the head excessively after the initial crank was deleterious to performance. Table 8-1 shows the selected measures that were analysed in the study. The base set of data were all stored in an Access (MS Office, 2016) database created for this purpose. This could be updated and queried as required enabling information to be sorted and selected as required. The methodology for angle measurement calculation has been previously described and validated [129][21].

Table 8-1 Kinematic variables calculated. See Figure 8-1 and Figure 8-2 for more detail.

Joint angle (max, min, range º)	Ankle, knee, hip, shoulder, elbow
Segment angle (max, min, range º) (measured relative to the global vertical)	Head, torso
Segment length (in set position)	Foot, shank, thigh, torso (hip joint centre to shoulder joint centre), upper arm, lower arm
Set position angles (º)	Joint – ankle, knee, hip, shoulder, elbow Segment – head, torso

All trials were analysed in Kinovea (version 0.8.15, and version 0.8.23) using 12 virtual markers as shown in Figure 8-1 to define the angles presented in Figure 8-2. The trajectory of each marker was traced through 150 frames (1.2 s) in Kinovea and exported using the Kinovea 2D reference system format. The path information for each marker was imported into Matlab (v 2018b, Mathworks®, USA). Segment vectors were constructed and then angles defined as per Figure 8-2 were calculated for each of the 150 frames. These were then plotted against time as per Figure 8-3.

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[21] Reprinted as Study 4

Figure 8-1 Virtual markers superimposed on the rider in Kinovea

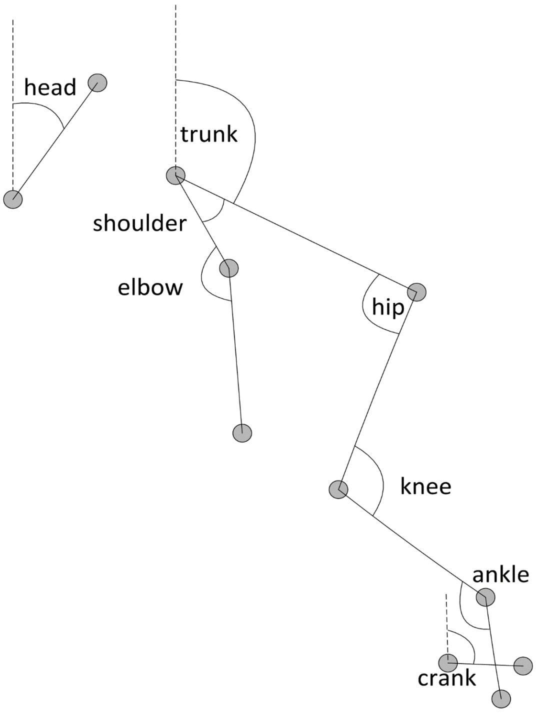

Figure 8-2 Angles generated from virtual markers in Matlab

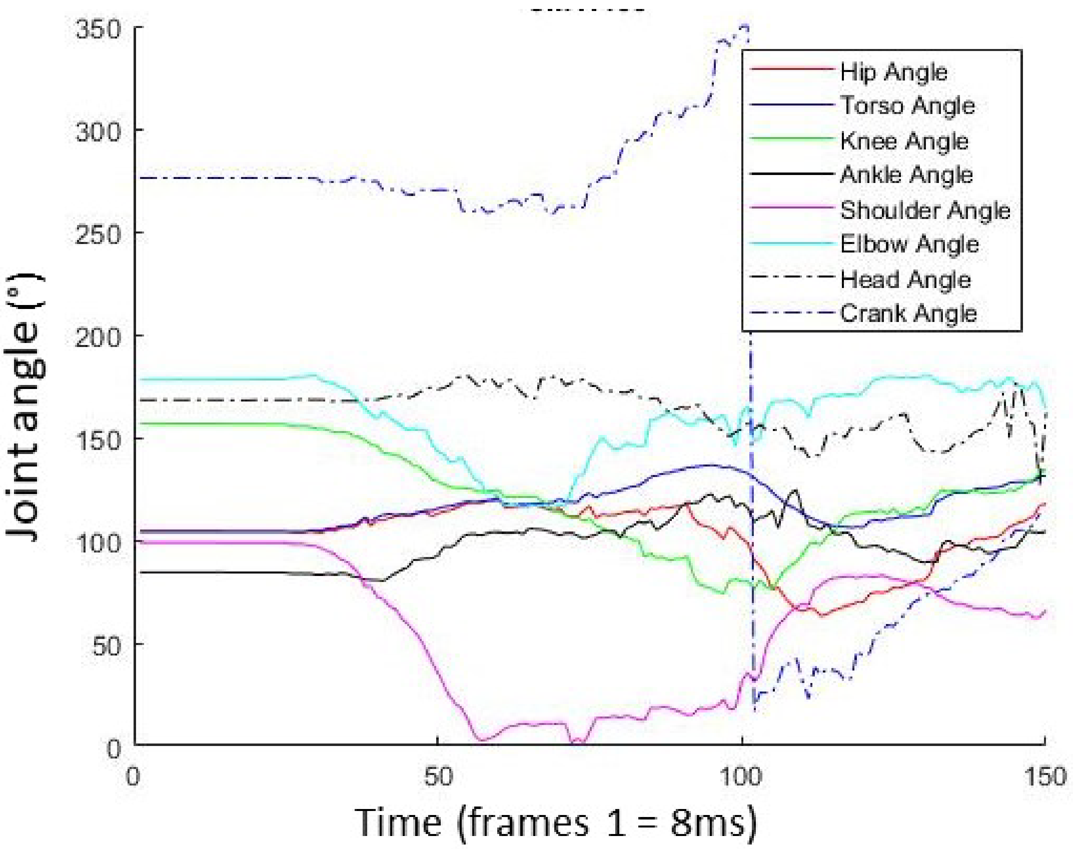

Figure 8-3 Example of joint, segment and crank angles plotted against time

The calibration factor was calculated by converting the measure of known item from pixels to m using Kinovea. The researcher held an item of known length in the middle of each lane at the height of the middle of the athlete/bike. This was filmed by the GoPro cameras in the data recording position. The filming of the object was repeated five times, each time on a different day. For each trial, the item was measured in each lane three times in pixels in Kinovea. The average was taken across all measures per lane. A calibration factor for each lane was calculated by dividing the known length (m) by the measured length in Kinovea (pixels) to give a m/pixel conversion factor. The calibration factor assumed that the bike/athlete is situated in the middle of the lane.

Distances such as segment length and hub height and recoil were based on a calibration formula (Equations 1 and 2). The number of pixels for each length was recorded as well as the ramp lane used by the participant for that trial

which was used to select the required calibration factor. The segment length was the average of the measure for each trial (*n* = 5) per participant.
The front hub height was calculated according to Equation 1.

$x\ is\ horizontal\ position\ in\ the\ Kinovea\ global\ coordinate\ system\ defined\ by\ pixels$

$y\ is\ vertical\ position\ in\ the\ Kinovea\ global\ coordinate\ system\ defined\ by\ pixels$

Equation 1 $Hub\ height = [max(x) - start(x)] * calibration\ factor$

The recoil was calculated according to Equation 2.

Equation 2 $Recoil = [max(y) - start(y)] * calibration\ factor$

8.4.3.2 Coaches' kinematic parameters

Parameters identified by CA's BMX head coach quantify elements predicted by the coach to be critical to obtaining a good race start. Any measures that could not be directly related to providing a quantifiable knowledge of performance were omitted. These parameters were based on discussions with coaching staff and further verified by reviewing coaching tips from online sources by high profile BMX coaches [189, 190] and are also similar to characteristics described in the research literature [14, 38]. Coaches' Parameters were:

1) time to gate edge (i.e. time at which front hub passes top edge of the gate),
2) front hub height as defined in Figure 8-4,
3) recoil as defined in Figure 8-5 and
4) hub trajectory as defined in Figure 8-6.

Minimising time to edge of gate and front hub height were thought to improve kink time performance. The relationship between kink time and rear recoil was considered potentially significant by the research team. The exact nature of these relationships had not been tested or quantified in any known published peer reviewed literature.

Figure 8-4 This figure shows the front hub at its maximum height. The hub lift is measured as the distance from the start height to the highest point on the hub trajectory.

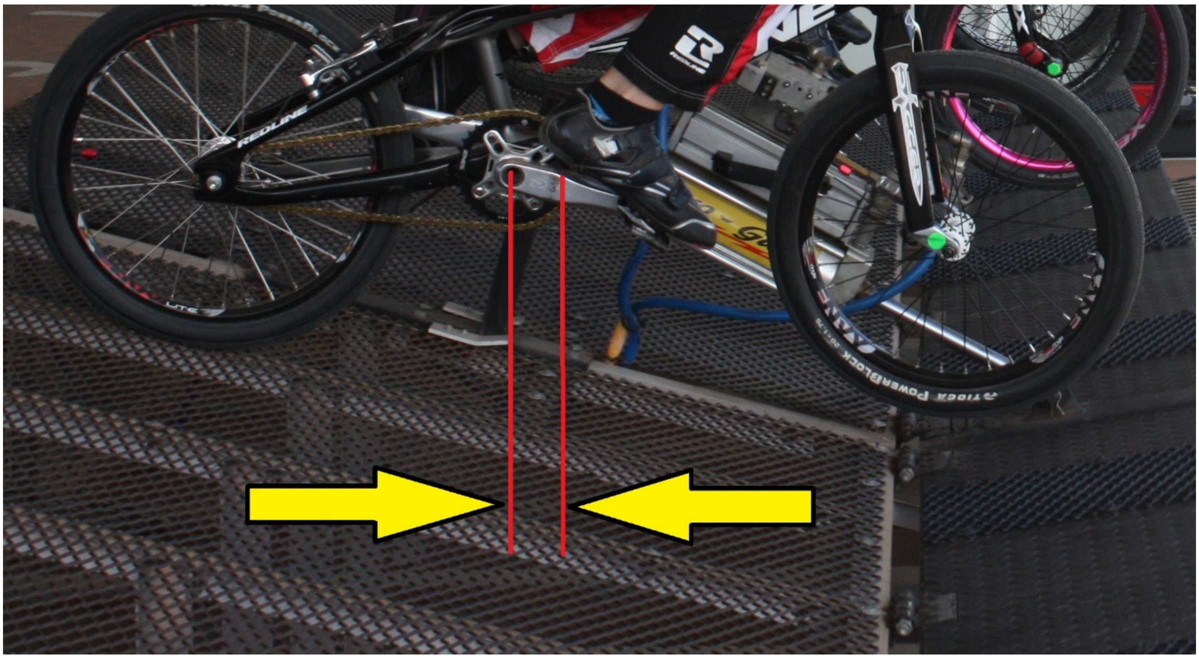

Figure 8-5 The first movement of the bike is backwards to counter the forward movement of the athlete. This was quantified by measuring the difference between the horizontal component of the starting position and the most backward position (most backward position shown here).

The hub trajectory refers to the shape traced by the front hub in the sagittal plane as shown in Figure 8-6. The wheel has to lift to go over the falling gate otherwise it may hit the gate and slow the movement, or even cause the athlete to fall over the handlebars. Coaches commonly describe a 'fast start' as having a '>' shaped front hub trajectory. The idea of the '>' trajectory is that there is minimal vertical wheel movement, allowing just enough height for the tyre to skim the top of the falling gate. To the student's knowledge, there is currently no known published data to substantiate this theory [127].

Figure 8-6 The hub trajectory is traced in red from the starting position in Kinovea.

8.4.3.3 Set position

The set position is the basis of the start action. In order to measure kinematics of the set position the joint angles from the second video frame following the start stimulus were recorded as the set position. The second frame was selected as this represented the position at 8 ms post start stimulus which is too early for a reaction to have occurred [100, 114, 115, 124]. The set position joint angles were recorded for each trial per athlete and mean ± standard deviation was calculated for each athlete and across the group. Common patterns were sought and used to define common set position ‘styles’ which were then used to categorise riders. These categories were formed by grouping the pictures together into naturally emerging groups and giving them descriptive labels that best described the athlete’s position. Ranges of shoulder and knee angle and position of the hip and head were also used to assist in the categorisation of the athlete’s set position.

8.4.3.4 Event heat map

In order to report the order of kinematic events, a heat map was created based on the time at which the minimum and maximum joint angles occurred for the ankle, knee, hip, shoulder and elbow joints and the torso segment. The heat map is a visual analytic tool that uses the concept of a chart that maps colour-to-event. This makes it easier to identify where events cluster. While not commonly used in sport science, this approach is common in fields such as engineering and is often used to display force distribution using finite element analysis enabling the identification of critical areas where force is likely to cause damage [191].

To create the heat map, the frame at which the minimum and maximum angle occurred was recorded for each joint. For some joints, it was possible to have two peaks of very similar height at either end of the trial of 150 frames. For example, in Figure 8-3 it can be seen that the elbow angle starts high, peaking at 178° at frame 1. It then peaks again at 180° at frame 112. In such cases the first trial may report a maximum elbow angle at frame 1, and another at frame 112. Averaging across the trials would then result in an average 56 frames which is actually close to when the minimum elbow occurred according to the plot. In such cases, the graphs were examined visually. Across the five trials the most common peak point was taken. For example, the five trials might have showed:

Frame for max elbow
Trial 1 – 1
Trial 2 – 10

Trial 3 – 130
Trial 4 – 5
Trial 5 – 135

The plots for trials 3 and 5 were examined and if a significant peak occurred in the 1-50 frames range and that value was within 5º (selected based on the measurement error reported in Grigg et al [128]) then the first peak value was used. The heat maps for each participant are summarised in Appendix 8 with each value that has been altered in this manner highlighted.

The frame numbers for the minimum and maximum events were averaged across all trials for each participant and converted to time in ms based on the frame rate of 120 FPS [128]. The events were placed in order and colour coded in a table. The participants were then arranged in order of average kink time and by order of rank as defined by CA BMX staff and coaches according to competition and race performance in the calendar year of data collection. The patterns were qualitatively examined with the aim of identifying movement patterns that may relate to kink time and athlete ranking.

8.4.3.5 Hub trajectory

The hub trajectory was traced in Kinovea by plotting the path of the front wheel hub, exporting the 2D coordinates of the hub pathway to Excel, calibrating the path from pixels to meters according to the calibration process described above and plotting all the paths for each athlete onto one graph in Matlab (2018b). The hub trajectory plots were examined for commonality within and between athletes, with ‘types’ of movement identified. The occurrence of the ‘>’ trajectory was sought and commented on. Common patterns of hub trajectory were sought which were then used to define categories. Each participant was assigned a hub type category based on the dominant shape observed in their hub trajectory plots. The observation was purely a visual analysis, where a ‘common’ hub trajectory shape was identified that was shared by all trials for the participant. It was recognised that this allocation was subjective, however the researcher tried to negate any bias by a) conversation with CA BMX coaches and staff, b) conversation with international coaches and c) reviewing blogs and training.

8.4.4 Statistical analysis

For each trial the range, minimum and maximum values of each joint and segment angle were calculated in Matlab 2018b. All parameters stored in the database were correlated to kink time using a two-tailed Kendall's τ_b and a Spearman's ρ in SPSS version 23 as per previous studies [69, 137, 151, 152]. The Kendall's τ_b was used to give an indication of ordinal association and Spearman's ρ was selected to identify monotonic but not necessarily linear relationships between parameters. The parameters were also correlated to each other, however only correlations to kink time were reported when significant. Correlations were graded according to recommendations from the literature [137, 150-152]:

- 0 - 0.19 very weak,
- 0.20 - 0.39 weak,
- 0.40 - 0.59 moderate,
- 0.60 - 0.79 strong and
- 0.80 - 1.0 very strong.

Variables included in the correlation analysis were:

a) ROM (head segment, torso segment, ankle, knee, hip, shoulder, elbow)
b) Maximum angle (head segment, torso segment, ankle, knee, hip, shoulder, elbow)
c) Minimum angle (head segment, torso segment, ankle, knee, hip, shoulder, elbow)
d) Frame at which maximum angle occurred (head segment, torso segment, ankle, knee, hip, shoulder, elbow)
e) Frame at which minimum angle occurred (head segment, torso segment, ankle, knee, hip, shoulder, elbow)
f) Segment length (foot, shank, thigh, torso, upper arm, lower arm)
g) Recoil – rear and front hub, and

h) Front hub height.

For each athlete the mean and standard deviation for joint and segment angles in the set position across all five trials were calculated and displayed in a box plot. The individual participant boxplots were retained and are presented in Appendix 8 for reference, with the boxplot of the collated data being displayed in the results.

8.5 Results

The results were summarised in tables and plots which were then cross referenced with each other in order to identify relationships between the various parameters that could be used to differentiate the faster participants' action and could be used to describe a 'fast' gate start action.

8.5.1 Kinematics - Correlation to kink time

Descriptive statistics from all parameters measured were presented in Table 8-2. The joint and segment angles were graphed against time for each athlete (see Appendix 8).

Table 8-2 Descriptive statistics of kinematic variables (n = 70 for all)

		Mean	Std. Deviation
Time split (s)	kink time	1.294	0.068
	time to gate edge	0.752	0.033
Angle (°)	max torso angle	141.6	7.0
	min torso angle	105.0	4.0
	max head angle	167.6	9.6
	min head angle	141.4	6.4
	max knee angle	154.8	13.5
	min knee angle	66.1	7.7
	max ankle angle	134.9	13.9
	min ankle angle	81.0	16.1
	max shoulder angle	91.9	5.4
	min shoulder angle	3.4	5.2
	max elbow angle	177.6	3.7
	min elbow angle	124.1	14.1
	max hip angle	132.1	9.1
	min hip angle	74.1	6.6
ROM (°)	ROM head	26.2	9.8
	ROM torso	36.5	6.5
	ROM hip	58.0	8.1
	ROM ankle	54.1	12.4
	ROM shoulder	88.5	7.1
	ROM elbow	53.3	14.8
	ROM knee	88.7	14.9
Timing of event (frame #)	frame # max hip angle	118.3	34.9
	frame # min hip angle	106.5	18.4
	frame # max torso angle	99.4	15.9
	frame # min torso angle	27.8	35.4
	frame # max knee angle	122.7	52.9
	frame # min knee angle	97.7	3.9
	frame # max ankle angle	130.3	29.8
	frame # min ankle angle	78.5	43.7

	frame # max elbow angle	59.4	51.1
	frame # min elbow angle	64.3	14.7
	frame # max shoulder angle	12.2	9.0
	frame # min shoulder angle	74.9	13.1
Distance (mm)	front hub height	160.9	40.1
	front hub recoil	103.1	47.2
	rear recoil	116.7	48.6
Segment length (mm)	length of torso	556.9	27.6
	foot length	257.4	283.8
	shank length	440.0	46.8
	thigh length	495.6	50.7
	upper arm length	299.2	32.3
	lower arm length	364.1	34.7

As shown in a sample plot of joint and segment angles against time (Figure 8-7), there are three distinct identifiable ‘shapes’ or events revealed by the kinematics; the set position, the position at the end of crank 1 (C1), and the position at end of crank 2 power stroke (C2PS). In the set position the body was stable as it responded to the start stimulus. At the end of C1 the athlete was at the top of the crank and ready to transfer weight from the lead leg to the second leg. The power stroke was a relatively long movement where maximum power was applied to the pedal by the front leg. These were described as the defining kinematic events of the gate start action.

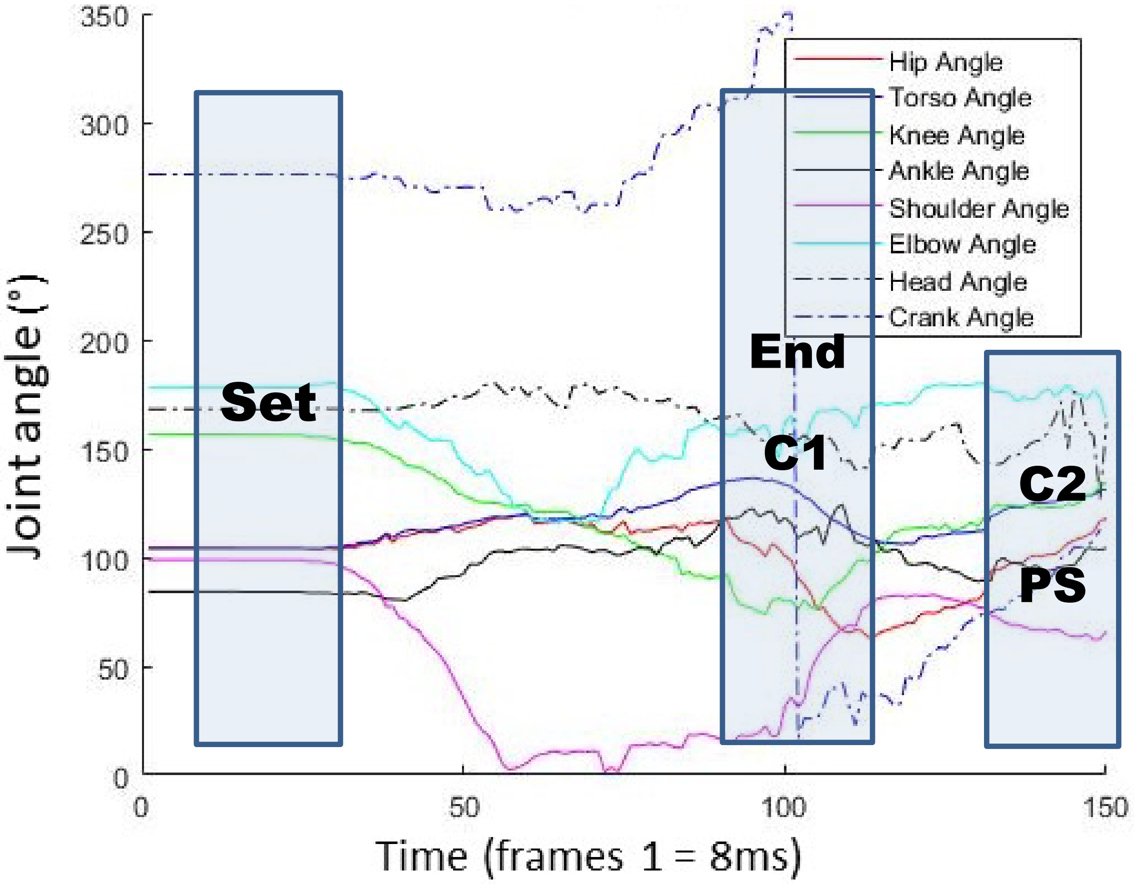

Figure 8-7 Sample of plot of joint angles to time with the three main identifiable events. Joint angle vs time.

The correlation of all variables showed that the most significant and meaningful parameters relating to kink time were the coaches' parameters (front and rear recoil) as shown in Table 8-3. The maximum shoulder angle had a weak correlation and typically occurs during the set position in most athletes. The maximum knee ankle was weakly/moderately related to ankle ROM ($\tau\_b = 0.32$, $\rho = 0.43$), and typically occurred at the end of the C2PS. The maximum knee angle had a strong correlation to knee ROM ($\tau\_b = 0.71$, $\rho = 0.87$) and typically occurred as part of the C2PS. Thus, the set position and the action of the power stroke had clear associations with kink time.

Table 8-3 Correlation to kink time. Only fair to moderate significant results are shown.

	Max knee angle	**Max shoulder angle**	**ROM ankle**	**ROM knee**	**Front recoil**	**Rear recoil**
Kendall's τ_b	-0.25**	-0.22**	-0.23**	-0.33**	-0.41**	-0.41**
Spearman's ρ	-0.38**	-0.29*	-0.34**	-0.49**	-0.60**	-0.58**

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Shading denotes correlation strength. Blue shading – ‘weak’, Yellow shading – ‘moderate agreement’, Red shading – ‘strong agreement’, Green shading – ‘very strong agreement’

Table 8-4 Significant meaningful correlations for front hub recoil and rear recoil.

		Kink time	**ROM torso**	**Max knee angle**	**Max shoulder angle**	**Frame # min elbow angle**	**Frame # min hip angle**	**ROM ankle**	**ROM knee**	**ROM shoulder**	**Front hub recoil**	**Rear recoil**	**Length lower arm**
Front hub recoil	Kendall's τ_b	-0.41**	0.18*	0.32**	0.42**	-0.20*	-0.20*	0.25**	0.29**	0.35**	1.00	0.82**	0.27**
	Spearman's ρ	-0.60**	0.25*	0.48**	0.58**	-0.30*	-0.28*	0.35**	0.30*	0.52**	1.00	0.95**	0.31**
Rear recoil	Kendall's τ_b	-0.408**	0.20*	0.37**	0.43**	-0.25**	-0.16	0.18*	0.26**	0.38**	0.82**	1.00	0.17*
	Spearman's ρ	-0.584**	0.26*	0.51**	0.56**	-0.35**	-0.27	0.28*	0.36**	0.54**	0.95**	1.00	0.25*

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Shading denotes correlation strength. Blue shading – 'weak', Yellow shading – 'moderate agreement', Red shading – 'strong agreement', Green shading – 'very strong agreement' [69, 137]

8.5.2 Set position

A summary of the set position for each athlete was presented in Table 8-5 and displayed in a boxplot in Figure 8-8. Individual athlete results displayed as box plots are in Appendix 8. The summary box plot shows that the head, knee and ankle angles exhibit the greatest overall variability in the set position, however the individual athlete data in Table 8-5 suggests that this was due to inter-athlete variability rather than intra-athlete variability. The greatest intra-athlete variation in head angle was 9.6° for participant 3, while the remainder of the athletes had a variation of < 4.1°. The greatest intra-athlete variation in ankle angle was 31.7° for participant 2, while the other participants had a variation of < 14.2°. Generally, variation for all other measured angles was < 5° across all angles, with the exception of participant 6, who varied between 12-17.4° for all angles except the head and elbow (which were both nearly always positioned at full extension).

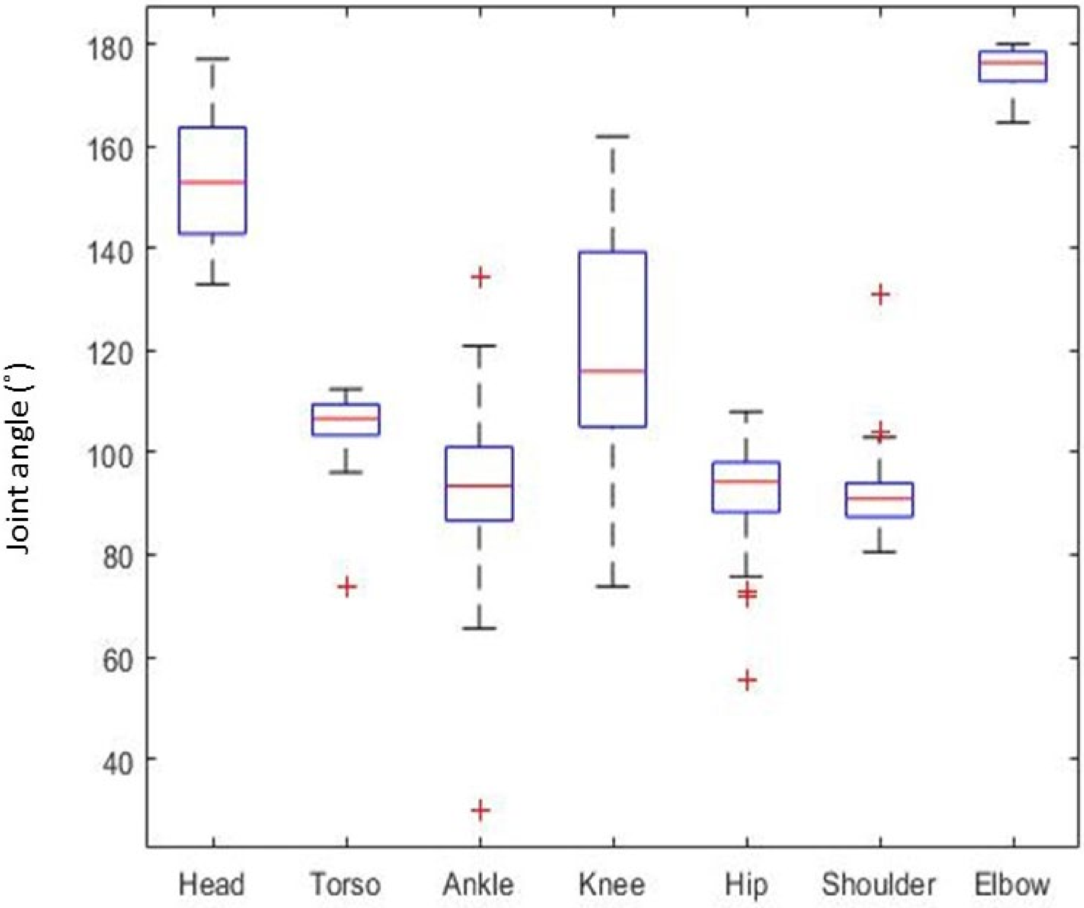

Figure 8-8 Summary of all participants set position, joints vs joint angles

Table 8-5 Summary of set position joint and segment angles (º) for all participants (Ave ± SD)

	Head (º)	**Torso (º)**	**Ankle (º)**	**Knee (º)**	**Hip (º)**	**Shoulder (º)**	**Elbow (º)**
1.0	149.2 ± 4.1	108.1 ± 1.9	90.8 ± 10.0	130.3 ± 3.2	92.4 ± 3.5	97.2 ± 4.1	178.0 ± 3.4
2.0	173.9 ± 0.7	101.3 ± 1.3	86.7 ± 31.7	101.3 ± 1.3	86.4 ± 2.1	93.4 ± 0.5	176.8 ± 2.0
3.0	145.0 ± 9.6	104.9 ± 3.7	105.7 ± 9.7	110.4 ± 10.5	77.9 ± 6.9	91.7 ± 3.8	169.0 ± 2.7
4.0	136.6 ± 1.9	99.4 ± 3.2	116.3 ± 14.2	150.2 ± 14.2	95.1 ± 1.9	95.9 ± 6.3	175.6 ± 3.5
5.0	156.4 ± 0.5	105.3 ± 2.0	94.4 ± 4.5	129.0 ± 5.1	90.8 ± 4.8	86.1 ± 5.9	171.8 ± 4.9
6.0	165.1 ± 3.5	104.2 ± 1.1	88.3 ± 6.2	155.7 ± 2.7	104.1 ± 2.5	93.5 ± 3.9	177.7 ± 1.9
7.0	141.5 ± 3.5	109.3 ± 0.6	100.0 ± 3.9	124.5 ± 3.9	90.5 ± 2.6	92.5 ± 2.8	175.5 ± 3.2
8.0	150.7 ± 3.4	99.0 ± 14.1	90.9 ± 12.7	138.0 ± 10.0	86.6 ± 17.4	106.1 ± 14.4	177.9 ± 2.9
9.0	144.7 ± 3.3	110.9 ± 1.7	97.4 ± 2.1	134.7 ± 8.2	100.0 ± 4.2	86.6 ± 3.9	177.3 ± 1.2
10.0	173.3 ± 2.5	109.1 ± 1.5	87.7 ± 4.8	139.5 ± 2.1	98.7 ± 3.1	87.0 ± 3.2	174.7 ± 3.6
11.0	143.3 ± 2.0	110.4 ± 0.9	102.1 ± 6.5	105.6 ± 4.1	85.5 ± 3.2	87.6 ± 3.4	175.6 ± 1.9
12.0	166.4 ± 2.2	103.6 ± 1.6	92.0 ± 1.0	140.8 ± 2.8	95.6 ± 1.4	88.8 ± 1.5	177.8 ± 0.9
13.0	160.7 ± 4.0	105.2 ± 1.8	90.7 ± 6.1	147.1 ± 6.5	98.2 ± 1.9	90.6 ± 2.2	169.9 ± 1.8
14.0	141.8 ± 1.4	111.1 ± 1.4	75.5 ± 6.9	137.0 ± 3.2	100.2 ± 2.2	86.0 ± 2.9	175.7 ± 3.7
SUMMARY	153.5 ± 12.6	105.8 ± 5.5	94.2 ± 13.9	122.2 ± 19.4	93.0 ± 8.7	91.6 ± 7.2	175.2 ± 3.9

As there were some inter-athlete variations in the set position, a visual inspection process was performed by the researcher, resulting in each athlete being allocated into one of three categories. The *back* style set position had a shoulder angle ~ 100°, bent rear knee ~ 135° and a relatively horizontal torso as per Figure 8-9. The *upright* style set position had a smaller shoulder angle ~ 90° and athlete was more forward on the bike with a straighter rear leg with larger ankle angle ~ 90° as seen in Figure 8-10. Figure 8-11 shows the *angled* style set position. This position was a blend of the two positions, with the bent rear leg of the *back*, and the smaller shoulder angle of the *upright*. Table 8-6 summarises the kinematic descriptors of the set positions and the allocation of each athlete's set position style. Table 8-7 shows the participant set style in order of kink time and then CA coaches' ranking. It can be seen that the *back* set position was favoured by the faster athletes, and the *upright* set position was favoured by the slower athletes.

*Figure 8-9 "**Back**" set position. The rider is back and down with a large shoulder angle, straight arms and bent knees.*

Figure 8-10 ***'Upright'*** *style set position. Straight arm, small shoulder angle and relatively straight legs. Body weight is forward.*

*Figure 8-11 "****Angled****" style set position - straight arms with a small shoulder angle and bent knee and small ankle angle. Body weight is forward, and torso is less horizontal.*

Table 8-6 Set style kinematic descriptors and categorisation of participants according to set position style.

Set Style	Torso (º)	Non-lead Knee (º)	Shoulder (º)	Participants
Back	~110	~130	>95	1,2,8
Upright	90-100	>135	~90	4,5,6,7,12,13
Angled	~110	~130	<90	3,9,10,11,14

Table 8-7 Participants set position style in order of kink time and coach ranking. Colour denotes back, angled and upright.

By kink time	Coach ranking
Back	Back
Back	Angled
Angled	Back
Back	Angled
Upright	Back
Upright	Angled
Angled	Angled
Upright	Upright
Angled	Upright
Angled	Upright
Angled	Upright
Upright	Upright
Upright	Upright
Upright	Angled

8.5.3 Event heat map

The event heat map in Table 8-8 shows the sequencing of the kinematic events of minimum and maximum joint and segment angles for all participants, ranked in order of average kink time. Table 8-9 presents the same data but has the participants in order of CA staff ranking at the time of data collection. As per Figure 8-7, three distinct 'events' can be seen, correlating to the set position, the position at the end of Crank 1 (C1), and the position at end of Crank 2 (C2) power stroke. In both heat maps, the set position was ~ 1 - 150 ms and was dominated by the lilac (maximum shoulder), pale red (minimum torso i.e. torso most horizontal) and dark yellow (maximum elbow). In both heat maps, the end of C1 occurred between ~ 500 - 850ms and was dominated by pale peach (minimum knee) and dark grey (maximum torso i.e. torso most vertical). The C2 power stroke, ~ 940-1200 ms, was characterised by the pale blue (maximum hip), light grey (maximum knee) and white (maximum ankle).

Table 8-8 Event heat map in order of kink time. Numbers in the cell are the ms from start to when the event occurs.

Subject	Ave kink (s)	1	2	3	4	5	6	7	8	9	10	11	12
8	1.198	133	141	318	429	632	749	774	853	862	1138	1149	1152
1	1.234	37	64	126	189	430	624	811	834	886	942	1099	1182
10	1.243	45	54	514	534	581	618	699	770	832	939	946	1155
2	1.247	8	8	8	541	632	778	811	902	960	1118	1203	1206
13	1.252	69	88	240	430	522	746	757	846	859	1166	1174	1184
12	1.261	83	88	274	531	686	792	901	909	954	986	1123	1123
11	1.273	123	154	331	373	435	494	728	758	875	1061	1162	1178
4	1.282	82	104	525	630	789	798	798	856	971	979	1168	1187
3	1.315	27	38	219	536	602	659	726	726	766	789	1202	1205
9	1.323	126	178	494	496	557	608	754	794	885	941	1166	1176
14	1.329	91	120	194	542	560	728	770	827	867	1179	1192	1195
7	1.371	59	192	298	514	618	646	754	778	882	1000	1083	1091
5	1.387	106	173	186	629	635	645	736	746	762	878	930	1197
6	1.401	59	130	142	162	320	494	549	642	774	810	906	1002

Max Torso	Min Torso
Max Knee	Min Knee
Max Ankle	Min Ankle
Max Shoulder	Min Shoulder
Max Elbow	Min Elbow
Max Hip	Min Hip

Table 8-9 Event heat map in order of coach defined athlete ranking. Numbers in the cell are the ms from start to when the event occurs.

Subject	Ave kink (s)	1	2	3	4	5	6	7	8	9	10	11	12
8	1.198	133	141	318	429	632	749	774	853	862	1138	1149	1152
3	1.315	27	38	219	536	602	659	726	726	766	789	1202	1205
1	1.234	37	64	126	189	430	624	811	834	886	942	1099	1182
9	1.323	126	178	494	496	557	608	754	794	885	941	1166	1176
2	1.247	8	8	8	541	632	778	811	902	960	1118	1203	1206
10	1.243	45	54	514	534	581	618	699	770	832	939	946	1155
14	1.329	91	120	194	542	560	728	770	827	867	1179	1192	1195
12	1.261	83	88	274	531	686	792	901	909	954	986	1123	1123
4	1.282	82	104	525	630	789	798	798	856	971	979	1168	1187
7	1.371	59	192	298	514	618	646	754	778	882	1000	1083	1091
6	1.401	59	130	142	162	320	494	549	642	774	810	906	1002
5	1.387	106	173	186	629	635	645	736	746	762	878	930	1197
13	1.252	69	88	240	430	522	746	757	846	859	1166	1174	1184
11	1.273	123	154	331	373	435	494	728	758	875	1061	1162	1178

Max Torso	Min Torso
Max Knee	Min Knee
Max Ankle	Min Ankle
Max Shoulder	Min Shoulder
Max Elbow	Min Elbow
Max Hip	Min Hip

8.5.4 Hub trajectories

The hub trajectories for each trial for each athlete are shown below. In each figure the athlete is moving from right to left (i.e. facing left). There are both inter-athlete and intra-athlete variations in hub trajectories. Examination of the plots in Figure 8-13, Figure 8-14 and Figure 8-15 suggested that there were no consistent clear relationships between trajectory shape and performance outcome within athletes for any athlete. For participants 1, 2, 5 and 14, the fastest trial had the most horizontal 'recoil' and the slowest trial had the least. However, this was reversed for participant 13. There was no clear relationship between max height of trajectory (vertical lift of hub) and kink time.

Based on visual inspection, there appeared to be three main shapes of hub trajectory as outlined in Figure 8-12. In comparing Figure 8-12 and Figure 8-13, Figure 8-14 and Figure 8-15 it could be seen that across the five trials per athletes there was consistency in trajectory shape for each athlete, suggesting that the dominant trajectory shape was a reflection of the attractor state of the athlete movement for the BMX WSX gate start action.

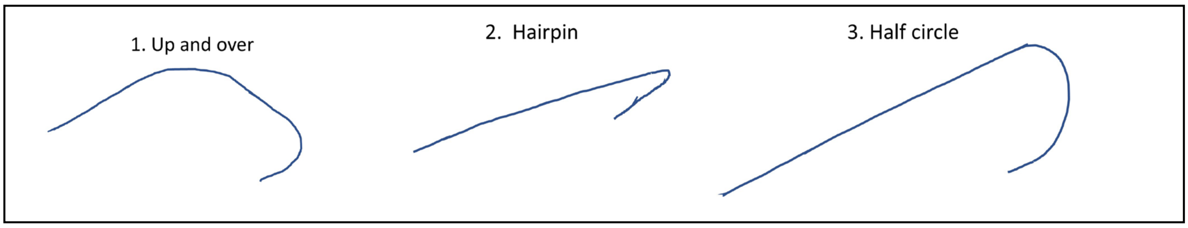

Figure 8-12 Hub trajectory types assuming that the athlete is moving right to left (←).

8.5.4.1 Up and over

The *up and over* is characterised by two 'bends'. The first is rearward facing as per the *hairpin*, but then the hub is lifted up further to create a second bend at the top.

8.5.4.2 Hairpin

The *hairpin* is a simple recoil and most resembles the '>' described by coaches. The athlete slings the bike backwards then moves forwards.

8.5.4.3 Half circle

The *half circle* is a larger smoother rounded shape than the other two shapes.

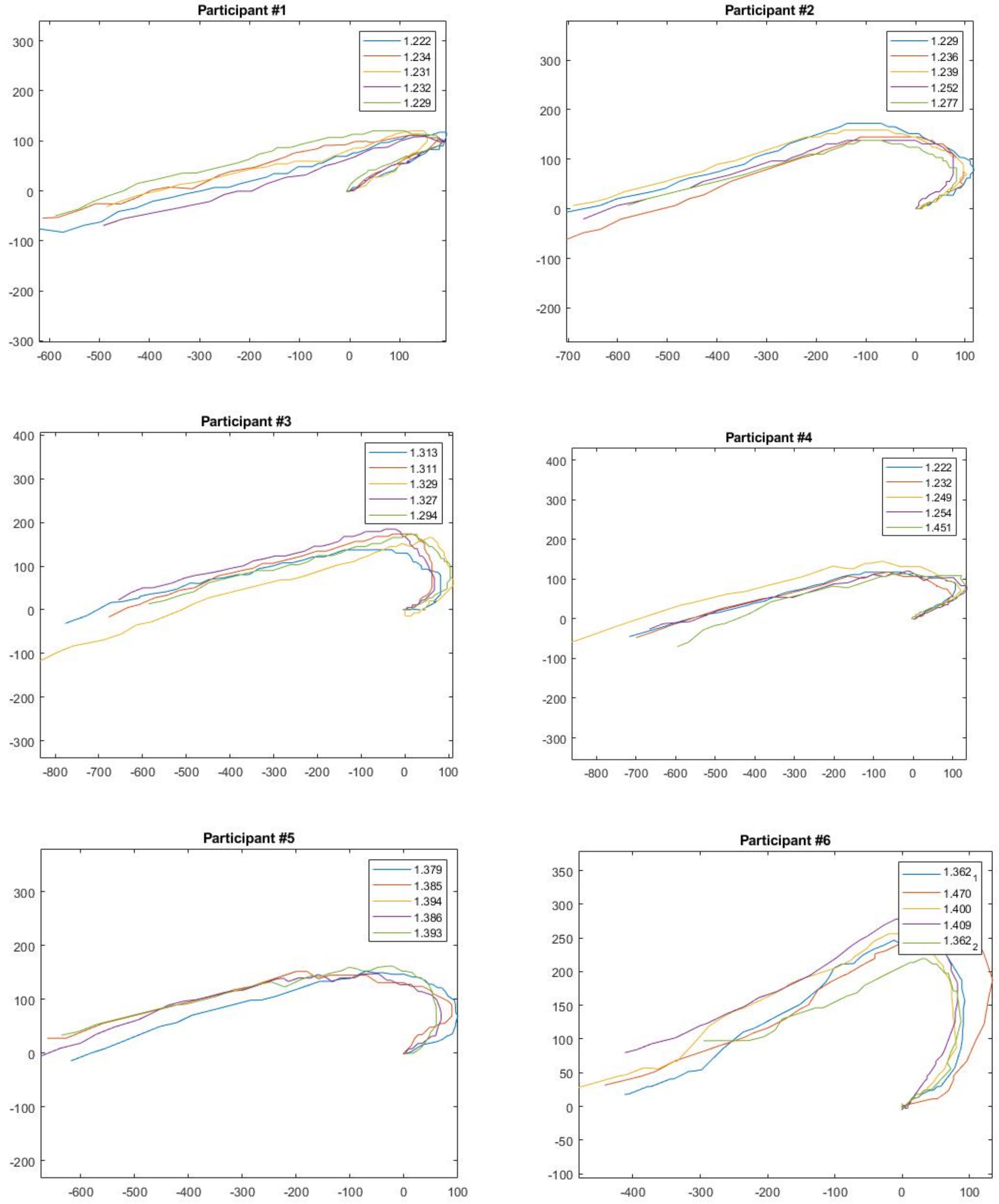

Figure 8-13 Hub trajectories of participants - a

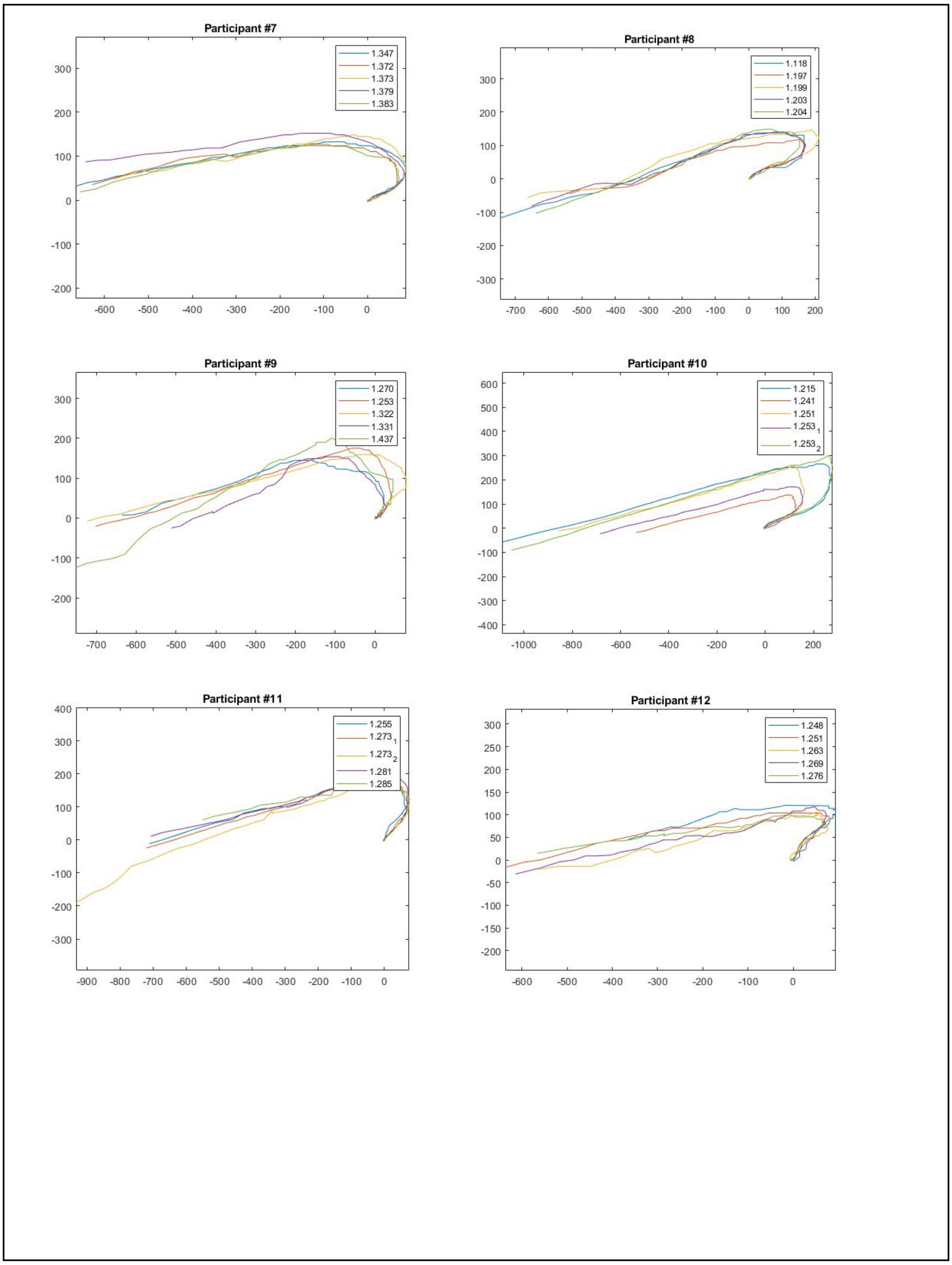

Figure 8-14 Hub trajectories of participants - b

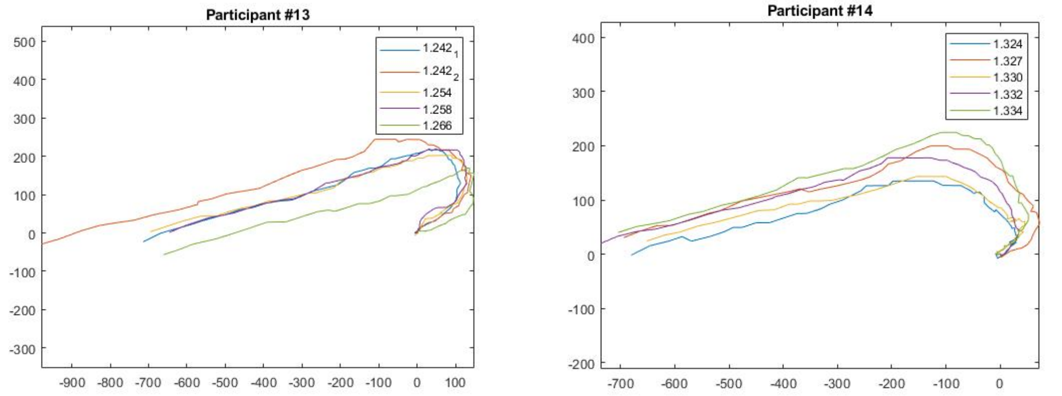

Figure 8-15 Hub trajectories of participants - c

Table 8-10 shows which hub trajectory category each participant was assigned to. As can be seen the participants were evenly dispersed between the three groups. Table 8-11 shows the category of trajectory of each participant, with the participants ordered firstly by average kink time of all five trials, and then in order of CA ranking. This simple categorisation approach suggested some association with the *hairpin* trajectory and a fast start, and the *half circle* was the least likely to produce a fast start. Three of the female athletes used the *half circle*, and one used the *up and over*, with the fastest female athlete using the *half circle*, and the second fastest using the *up and over*. The *hairpin* was close to the '>' described by coaches as the preferred shape for a 'fast start'. These results appear to confirm the coaches' theory that a *hairpin* '>' style hub trajectory was preferable for a fast gate start.

Table 8-10 Participant allocation to hub trajectory category.

Hairpin	Up and Over	Half Circle
1	2	3
4	5	6
8	9	7
10	12	11
	14	13

Table 8-11 Category of trajectory by participant order in a) fastest kink time and b) CA coaches' ranking. Blue – Hairpin, green - Half circle, orange – Up and over

By kink time	By CA ranking
Hairpin	Hairpin
Hairpin	Half circle
Hairpin	Hairpin
Up and over	Up and over
Half circle	Up and over
Up and over	Hairpin
Half circle	Up and over
Hair pin	Up and over
Half circle	Hairpin
Up and over	Half circle
Up and over	Half circle
Half circle	Up and over
Up and over	Half circle
Half circle	Half circle

Table 8-12 Athlete hub trajectory category and set position style in with participants ordered by min-max kink time then highest – lowest coach ranking. Colour denotes specific pairings e.g. blue = Hairpin Back

By kink time	By coach ranking
Hairpin Back	Hairpin Back
Hairpin Back	Half circle Angled
Hairpin Angled	Hairpin Back
Up and over Back	Up and over Angled
Half circle Upright	Up and over Back
Up and over Upright	Hairpin Angled
Half circle Angled	Up and over Angled
Hairpin Upright	Up and over Upright
Half circle Angled	Hairpin Upright
Up and over Angled	Half circle Upright
Up and over Angled	Half circle Upright
Half circle Upright	Up and over Upright
Up and over Upright	Half circle Upright
Half circle Upright	Half circle Angled

8.6 Discussion

The aim of this study was to use kinematics to describe a ‘fast’ gate start as described by the minimum kink time for 14 WC and Elite BMX athletes. The parameters most likely to correlate to performance, that is kink time, were front and rear recoil, which related to the backwards motion of the bike during the slingshot phase (τ_b= -0.41 for front and rear recoil, and ρ = -0.60 and -0.58 for front and rear recoil respectively). The larger the front and rear recoil, the faster the gate start. This suggested that the initial backward movement of the bike could be used as a performance indicator for kink time. This is an easy parameter for a coach to measure with a simple tool such as Coach’s Eye (TechSmith Corporation, U.S.A.) on a smart device. Table 8-4 shows the kinematic parameters that correspond to both front hub recoil and rear recoil. Front hub recoil and rear recoil corresponded strongly to each other (τ_b = 0.82, ρ = 0.95). This correlation was expected given that the two points are connected by the bike frame. It was possible for the front hub to recoil further than the rear hub as the handlebars (front wheel) were lifted vertically. The rear wheel always remained on the ramp.

The larger the knee ROM the faster the gate start (τ_b = -0.33, ρ = -0.49). A large knee ROM was associated with maximal knee extension (τ_b = 0.71, ρ = 0.87) which occurred during the C2PS event. Maximum hip and ankle angles also occurred in the C2PS event (Table 8-8). Thus, the C2PS event for a ‘fast’ gate start can be described as full extension through the hip, knee and ankle (plantarflexion) to create a large sweeping power stroke action to apply maximal torque to the pedal.

Mapping patterns within the kinematics of the set position enabled identification of three different set positions, *back*, *upright* and *angled*, with the *back* set position preferred by better performing i.e. faster, athletes. The hub trajectory maps enabled the identification of three common patterns, or shapes: *hairpin, up and over* and *half circle*. The better performing athletes produced a *hairpin* trajectory. Clear trends indicated that performance was optimised with a *back* set position and a *hairpin* hub trajectory. Thus, a ‘fast’ gate start is characterised by a *back* set position, moving into a larger recoil movement, then tracing a hairpin trajectory with the front hub and ending with full knee and ankle extension (plantarflexion) through the C2PS.

These results suggest that only a subset of the parameters that were measured in this study are needed to describe a ‘fast’ gate start. Further research and the development of training tools could focus on just these most meaningful parameters. Given the overall aim of describing a ‘fast’ BMX SX gate start these results suggest that key measures are

a) the timing of maximum/minimum joint angles,
b) distance of rear hub recoil,
c) kinematic description of the set position, namely shoulder angle, rear knee angle and torso angle, and
d) the shape of hub trajectory.

While BMX coaches have substantial practical experience and intuition about what characterises BMX gate start performance and the factors that may improve this aspect of BMX racing, there is still very little peer-reviewed research in this area with which to compare the findings presented here. The most recent study in BMX SX gate start kinematics by Gross et al [16] assessed nine internationally ranked riders who each performed five individual gate starts on an 8 m ramp with a standard SX gate start procedure. The riders wore tight fitting clothing and were fitted with retro-reflective markers for full body 3D motion capture with a 20 camera Vicon system. Time splits were taken at the base of the ramp and then 5 m directly after on a flat sprint section. Gross et al [16] reported knee joint angles of ~ 75 - 170˚ (ROM 95˚) and hip joint angles ~ 80 - 155˚ (ROM 75˚) which compared favourably to the averages reported in Table 8-2 (knee angle = 66.1 ± 7.7 - 154.8 ± 13.5˚, ROM 88.7 ± 14.9˚, hip angle = 74.1 ± 6.63 - 132.1 ± 9.1˚, ROM 58.0 ± 8.1˚). Further analysis by Gross et al [16] indicated that athletes who began the forward movement earlier reached the base of the ramp sooner, although this was not necessarily related to the recoil. Gross et al [16] theorised that more proficient athletes reached the most backward position (end of the recoil movement) earlier than the other athletes and then directed the forward thrust to the greatest advantage to allow for maximal speed whilst still clearing the gate. A variation in velocity at the base of the ramp was seen (between 93 - 96% across all athletes) which was attributed to the power applied to the pedal on the first stroke and the velocity as the athlete passed the gate [16]. The kinematic data presented in Gross et al [16] was collected with the athletes in tight fitted clothing and on a bespoke training ramp that was narrower than a normal SX ramp which did not lead onto a track, but onto a flat straight. This difference in conditions may have significantly altered the athlete kinematics because of the reduced safety, difference in need to generate speed at the base of the ramp in order to tackle a jump and the different feel of tight clothing.

Kalichová et al [45] examined joint angles in the sagittal set position for one trial each of two international BMX competitors on a training start ramp (height < 5 m). The large shoulder extension on the left side for both athletes suggested a *back* set position was used. Kalichová et al [45] reported the joint angles at the end of each of the phases defined in Kalichová et al [45], rather than minimum and maximum angles as reported in this study. The smallest - largest knee angle (88 - 168˚), hip angle (93 - 137 ˚) and shoulder angle (35 - 101˚) reported in Kalichová et al [45] are comparable with the findings in this study (Table 8-2). It can be seen that the joint and segment angles reported in here in Table 8-2 appear reasonable, and that each athlete is somewhat distinct in their execution of the gate.

While no other known studies have investigated hub trajectories or set positions, there are many theories postulated by CA coaches. The most common is the relationship between the '>' hub trajectory and kink time. This shape is much like the *hairpin* described in this study which appears to be most likely to produce a fast kink time. These results validate the CA coaches' theory that the '>' is the most desirable hub trajectory shape. The impact of the set position is much debated by coaches and there is currently no known published research on this topic. Different coaches have differing opinions however the CA BMX head coach prefers the *back* set position believing that it puts the athlete in the most advantageous position to generate forward momentum (Wade Bootes, personal communication, 28 August, 2018).

8.6.1 Translation to coaching

The manner in which the key measures for describing a ‘fast’ gate start were interpreted for the application by coaches and athletes is now discussed.

8.6.1.1 Set position

The set position is the basis of the movement through the gate start action. In the gate start, the athlete needs to find a balance point on the bike yet be in the optimal position to initiate a powerful movement in response to the gate start reaction stimuli. As seen in the heat maps in Table 8-8 and Table 8-9, this is characterised by the athlete adopting a position characterised by a minimal torso angle, and maximal elbow and shoulder angles (extension). A number of correlations also supported the importance of the set position for minimising kink time. For example, maximal shoulder angle correlated to kink time (τ_b= -0.22, p = 0.01, ρ = -0.29, p = 0.05), indicating that the set position is important for performance outcome, with a large shoulder angle relating to a faster kink time. The frame at which maximal shoulder extension occurred correlated to the frame at which the minimal torso angle occurred (τ_b= 0.26, ρ = 0.32, p = 0.01). The maximal shoulder angle correlated to the minimal torso angle (τ_b= -0.32, ρ = -0.42, p = 0.01). This describes a set position where the athlete is ‘back and down’ in the *back* set position as per Figure 8-9. For the athlete pictured in Figure 8-9, the maximum shoulder extension angle (91.6 ± 7.2°) occurred at the same time as the minimum torso angle (105.8 ± 5.5°) and the athlete was positioned over the rear half of the bike. When the athlete set position was displayed in order of kink time there appeared to be a relationship between the set position style and kink time, with the *back* position being used by the faster participants as shown in Table 8-7. When the participant set style was mapped to the hub trajectory category as per Table 8-12, it was demonstrated that the fastest and highest ranking athletes both used the *back* set position and had a *hairpin* style hub trajectory. The slowest combination appeared to have been the *upright* set position with the *half circle* hub trajectory.

In his vlog on gate starts for beginners, 2016 Olympic Gold medallist Connor Fields used a bent non-lead knee set position and set the body back as per the *back* position. He described driving the whole body forward through the start action [183]. Mr Fields said that some coaches teach a 'hip drive' method where the focus is taking the hips to the handlebars and that this leads to the body lifting up high (i.e. making a large torso angle), but this is not advisable as the overall movement of the bike and athlete is 'up' rather than 'forward'. From an energetics perspective this makes sense as the centre of mass (COM) has the least discursion from start point to end point when the body retains a more horizontal torso position through the gate start action as per Figure 8-16. This suggests that the faster WC athletes have developed an action that is more efficient in maximising movement in the direction needed during the initial phases of the gate start, in which they have to negotiate the drop of the gate and propel the bike down the ramp. When the athlete drives the COM forward from the *back* position, the direction of the resultant force as shown in the arrow in Figure 8-16 would result in a rearward recoil (as per Newton's third law of force, for every action there is an equal and opposite action). The *upright* and *angled* set positions both would result in a more upward movement of the COM meaning that a component of the resultant force acts downward as shown by the force arrow in Figure 8-17, resulting in less rearward recoil. Considering the demonstrated negative correlation between recoil and kink time, it can be surmised that the set position producing the greatest recoil (*back* set position) may produce the fastest kink time, which was supported by listing the athletes' set position in order of kink time (i.e. Table 8-7).

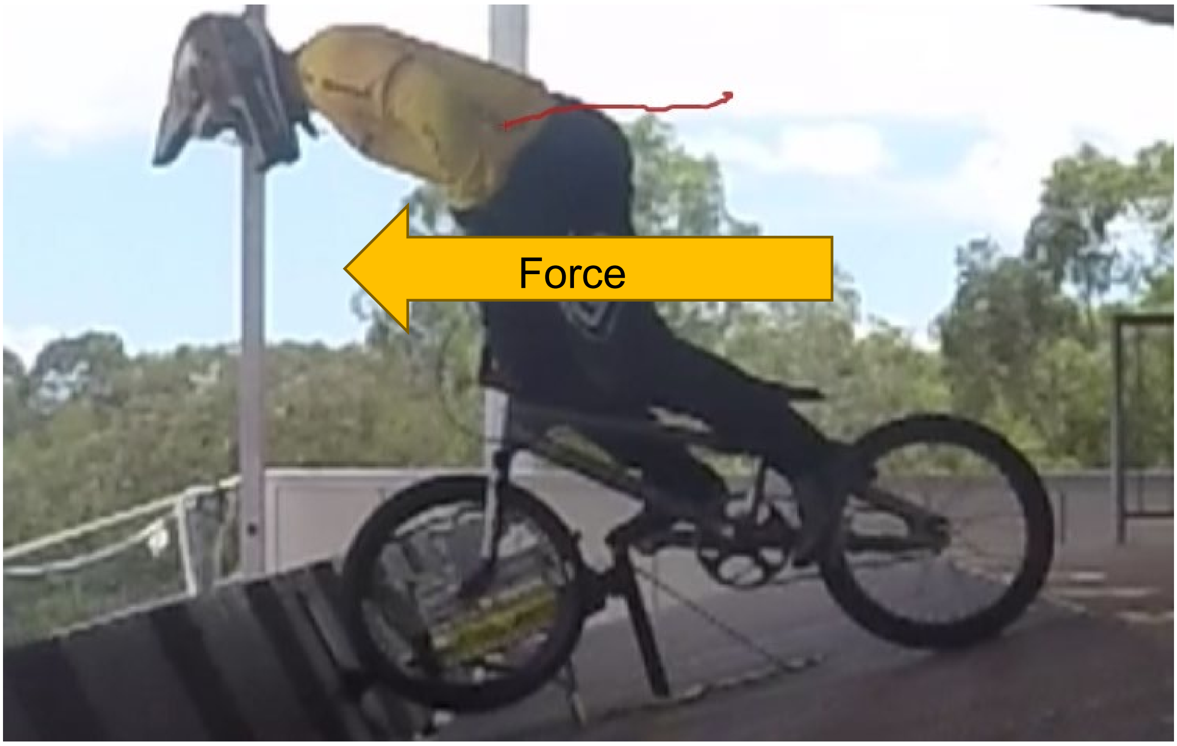

*Figure 8-16 The trajectory of an approximated COM is shown in red. It is almost a straight horizontal like in this case where the athlete starts with a **back** set position and has a **hairpin** trajectory.*

*Figure 8-17 This **upright** starter who then goes into a **half circle** hub trajectory has a larger COM discursion with a vertical component.*

8.6.1.2 End of C1

The *half circle* hub trajectory and *upright* set position combination can result in a problem at the end of C1, the second key event identified in Figure 8-7. From an *upright* set position the athletes lifted the torso to the maximum torso angle as per Figure 8-18 while drawing the handlebars to the hips using shoulder extension to the minimum shoulder angle. This resulted in the handlebars moving very close to the thighs as seen in Figure 8-19. In this position there was not much room to bring the second leg (in this case the right) through to the top of the second crank. This meant the athlete needed to move the body backwards relative to the bike to make space behind the handlebars to bring the leg through for the second crank. This could have caused the ‘bend’ seen at the top of the *up and over* hub trajectory. Observed movement solutions involved the athlete rotating the leg laterally by abducting and externally rotating the hip or tilting the bike away from the side of the leg coming forward. These actions could be easily observed by standing behind the athlete. Another issue with the *upright* set position that may have contributed to slower kink times was that the COM moved up and the forward thrust was reduced so the recoil distance was relatively small. In this case the COM may only have come forward as pedalling started.

Figure 8-18 Rider raising the torso to vertical to lift the front hub up. Athlete has left leg as the lead leg.

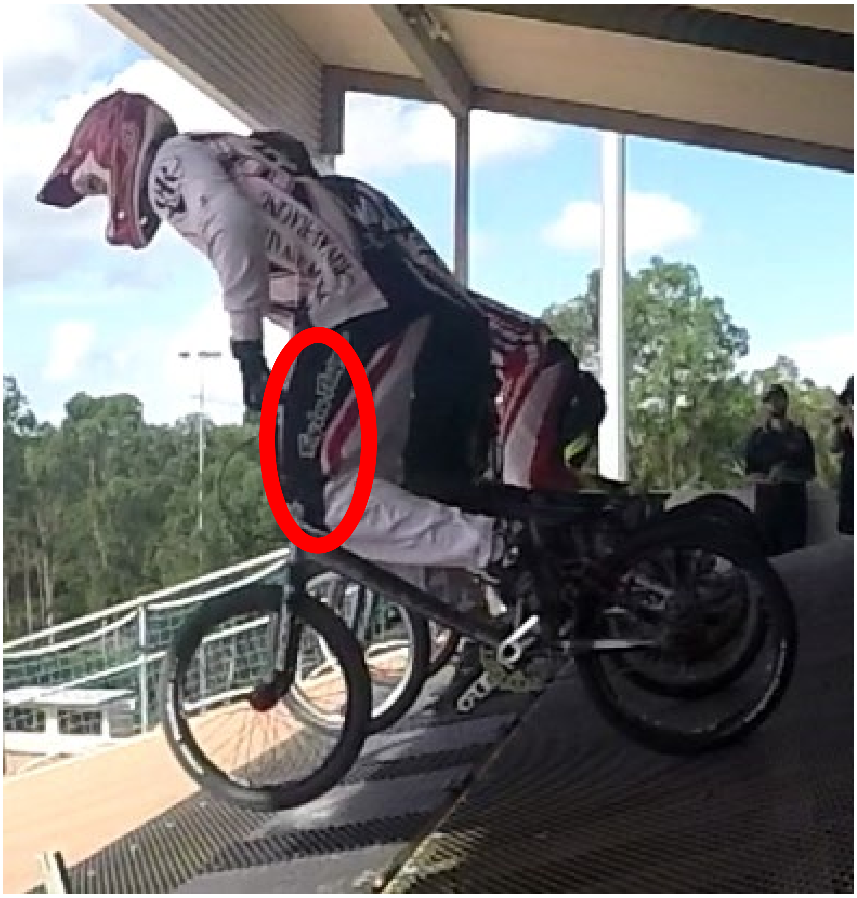

Figure 8-19 The athlete does not have room between the handlebar and the thigh to pull the second leg through.

8.6.1.3 C2 Power stroke

The third critical event was the C2 power stroke. This was characterised by the maximal ankle, knee, and hip angles (i.e. full extension at each joint of the limb to execute the power stroke - i.e. plantarflexion at the ankle). Mechanically this makes sense as it utilises the full capacity of the extensors at the hip, knee and ankle to produce a maximal summation of force at the distal end (i.e. at the crank) [192]. As can be seen in Table 8-3 and Table 8-4, this extension of hip, knee and ankle correlated weakly/moderately to kink time (ROM ankle $\tau_b = -0.23$, $\rho = -0.34$, ROM knee $\tau_b = -0.33$, $\rho = -0.49$) and rear recoil (max knee angle $\tau_b = 0.37$, $\rho = 0.51$). This implies that maximising the triple extension of hip, knee and ankle (i.e. plantarflexion) through the power stoke is a key performance characteristic of a fast gate start.

8.6.2 Limitations

This study was designed to address some of the major gaps in the literature, particularly with respect to the relatively low number of participants recruited and trials analysed as well as the questionable ecological validity of the data collection and validity and reliability of the data analysis process. However, there were still some limitations that should be acknowledged.

A larger number of WC athletes may have provided more robust results regarding performance characteristics of the faster athletes. While all Australian WC athletes in the period 2014 - 2018 were tested, there was no access to WC athletes from other countries, which is a common challenge when working in research with high level professional athletes. More trials per athlete may have provided greater certainty regarding intra-athlete variation and the impact of variation of different parameters on kink time. There is also a small, but potentially important systematic error due to the nature of markerless motion capture as discussed in Grigg et al [129]. The gold standard of motion capture remains 3D motion capture as per Gross et al [16], however this is not only costly, but because the BMX athletes can not wear their normal protective clothing during 3D analyses, there was concern that the action may be altered due to variations in the feel of the clothing and the reduced athlete safety without the bulky protective equipment.

8.6.3 Implications

The results of this study have a number of strong implications for improving BMX gate start performance. If the recoil is significantly related to kink time, then training to maximise recoil may result in a decrease in kink time. Similarly, recoil could be used to monitor gate start training where no timing system is available. This is an easily measured parameter which can be monitored by coaches and athletes to form part of a training history. It could also be used to help optimise bike setup and as a form of augmented feedback to the athletes.

The set position and hub trajectory categories can be used to classify athletes and help athletes understand their own performance. Teaching development level coaches how to identify these set positions and how they relate to gate start performance may help improve lower level BMX athlete results. This educational rollout has already commenced with the researcher presenting the categorisation of gate starts and hub trajectories to a conference of coaches and riders at the national level in Australia. Further training workshops with BMX Queensland are under development. These will include the definitions of the different set styles, the likely impact of set position on gate start performance and how to identify an athlete’s preferred set style.

The ROMs and the timings in the heat map could be used to approximate average joint angular velocity, which together with the ROMs could be used for exercise prescription by strength and conditioning coaches. This information may help in the selection of the most appropriate activities to develop the force-power-velocity characteristics required for the BMX SX gate start action. There currently appear to be relatively few strength and conditioning coaches with a BMX racing specialist interest, however this area of off track training is growing with the understanding of the importance of power development in the first few cranks for performance outcome [12, 145, 147, 193].

8.6.4 Further areas of research

The research presented in this PhD thesis may form the basis for further study. Future research may be facilitated by the novel use of technologies, such as inertial measurement units (IMUs) that can be attached to a body under safety clothing and can be used to measure 3D movement. The disadvantage is that the software used to interpret the output of such devices may be cost prohibitive or need to be further developed by the user. The Dutch BMX team who train at the Sportcentrum Papendal had access to a Xsens (© Xsens, The Netherlands) IMU system and have trialled the Xsens on a SX ramp. The Australian athletes have been invited to trial this system when they are next in Papendal. This would present an opportunity to compare 3D data with data presented in Studies 4 and 5. The Xsens system was developed for video gaming and is currently being further developed for sports biomechanics. Future research may examine the validity and reliability of IMUs like the Xsens and compare this to traditional 2D or 3D motion capture so to determine the relative strengths and weaknesses of all these methods relative to each other for field research and coach/athlete support.

It was not possible to complete a skill acquisition intervention in which technical parameters such as start position or hub trajectory were altered as part of this particular PhD due to time constraints. However, the results of the present study would inform future research where a participant with an *upright* or *angled* set position could be trained to transition to a *back* set position. Such a study could provide important information on the ability and training required to change set position and whether this has direct implication for kink time. The researcher has seen coaches making such changes to an athlete’s set position with considerable improvements in kink time being observed.

Future research could investigate the impact of trends in coaching history, injury history and anthropometry that may have contributed to athletes selecting and utilising a given gate start action style. This could give insight into the coaching cues that lead to the development of more efficient gate state start actions and inform coaching methodology.

8.7 Conclusion

This study found an inverse relationship between bike recoil and kink time for the BMX SX gate start, whereby the greater the recoil the smaller the kink time. This information could be used by athletes and coaches to monitor gate training in the absence of timing systems by measuring the recoil of the back wheel with a simple smart device app such as Coaches' Eye. The set positions performed by 14 WC and Elite athletes could be categorised as *back*, *upright* and *angled*, based on the shoulder angle, rear knee angle and horizontal angle of the torso. These positions may influence the front hub trajectories as the bike passes over the gate, with the *back* set position most likely to result in the fast *hairpin* trajectory, while the *upright* set position is more likely to produce the slower *half circle* trajectory. This information may be used by coaches to assist development athletes to improve their technical proficiency of the gate start action.

Chapter 9: Discussion

9. Discussion

The overall objective of this PhD was to perform a biomechanical analysis of the BMX SX gate start in order to inform coaching, sports science and strength conditioning support of BMX athletes. This was achieved by addressing two complementary aims: a) to describe the phases and key spatiotemporal biomechanical determinants of the BMX SX gate start so to gain additional insight into the movement characteristics for optimal performance, and b) to investigate potential differences in movement patterns between World Class and Elite as well as male and female BMX athletes. These studies provide a greater understanding of the movement characteristics that relate to optimal performance of the BMX SX gate start, as described in Figure 9-1.

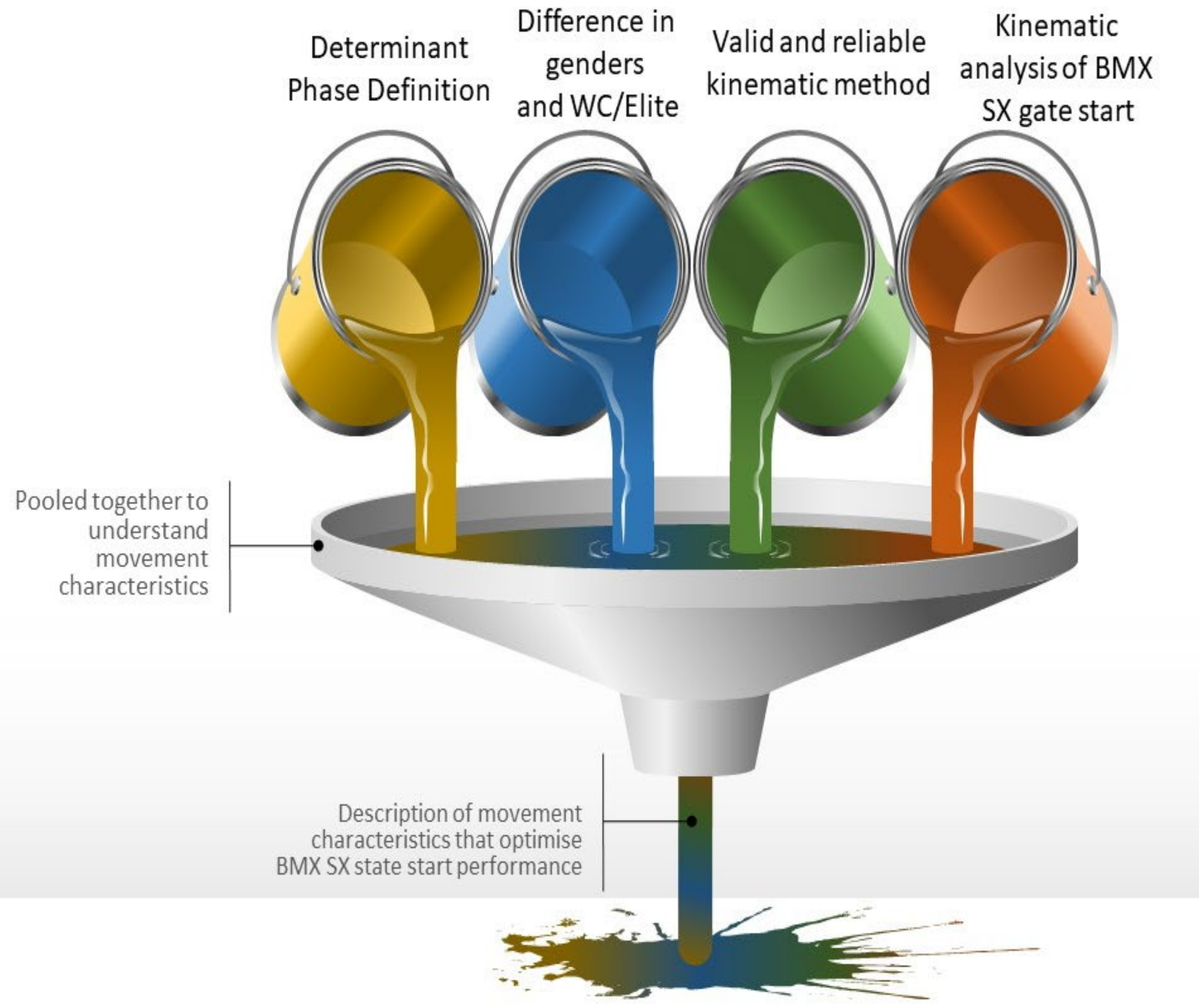

Figure 9-1 Summary figure of studies and overall outcome of the program of research

This program of research used 2D motion capture analysis and a reaction timing device to a) define determinant phases of the BMX gate start, b) measure RT and c) measure athlete kinematics. These measures were then used to a) define the difference between male and female athletes, WC and Elite athletes, b) measure the effectiveness of a RT training intervention and c) examine relationships to kink time (performance outcome).

9.1 Alignment with the research community

In order to build a rigorous scientific body of research, it was necessary to use a robust methodology previously accepted in literature. It is accepted practice in biomechanics research to break a complex action into subcomponents and to use this to further investigate movement differences between cohorts and to inform study into detailed kinematic analysis [18, 59, 184]. This PhD research project followed this model, starting with an investigation into the phases of the BMX gate start action, and ending with a detailed investigation into the kinematic description of a 'fast' gate start.

To date only three known peer-reviewed studies have investigated the kinematics of the BMX gate start [16, 38, 45] and considered the relationship between kinematics and performance outcome. These studies described the forward movement of the bike [38], body segment movement [45], speed generation down the ramp and hip and knee sagittal kinematics [16]. While multiple number of trials were performed per athlete in each of these three studies, only one trial per athlete was analysed. No validity or reliability data were referenced for the methodology used in any of these studies, although the third study by Gross et al [16] did use the 'gold standard' 3D marker motion capture system. The only precedents available to form a starting point for this PhD project were the first two pilot studies mentioned above, that each used 3 or fewer participants, analysed only one trial per participant and did not use a standard SX ramp. Gross et al [16] was published after the majority of this PhD project was completed. This PhD is the first known published, thorough investigation of the biomechanics of the BMX SX gate start action.

The reaction time intervention study (Study 3, Chapter 6) was similar in design to that presented by Papic et al [124]. As per the Papic et al [124] study in swim start reaction time and other reaction time training studies [102, 124, 159, 166] the intervention was specific to the activity with the aim of improving performance, be it race start performance, balance maintenance or muscle activation. Study 3 is the first known RT training study to be conducted in cycling and lays the foundation for further research in this area. Relevance of this thesis to coaches

The questions raised in this PhD project were developed in collaboration with CA coaches and staff. To provide meaningful answers to the posed questions for CA, a high degree of ecological validity was considered imperative. Studies show that laboratory tests results do not always correlate to on-field performance [51, 54, 86]. In the case of BMX, the psychological component associated with performing a maximal intensity gate start on 8 m high ramp with other athletes may have a significant impact on movement characteristics because of the height of the ramp, the camaraderie of the participants and the general competitive atmosphere during a training session.

Advances in video camera technology have enabled markerless motion capture in situ to become more accessible in field research [80-85], with the recommended frame rate (≥ 60 FPS) and high definition picture quality (> 640 x 480 pixels) becoming more readily available [10, 87]. This allows for the activity to be performed in a realistic manner where the task constraints such as using a real BMX bike on an Olympic standard gate and where the environmental constraints such as weather, peer pressure and equipment can be very similar to that seen in competition. The methods used in this project can be applied by coaches and athletes using relatively inexpensive action cameras, tablets or smart phones. This means that they can incorporate findings of this study into their daily practice, thereby fulfilling the aim of creating a resource that is meaningful for coaches for improving gate start performance, prescribing off-track training, talent identification, movement monitoring, etc.

9.2 Summary and practical applications

Figure 9-2 shows the sequence of the studies and how they interact. In the first project in the PhD (Study 1) the determinant phases of the BMX SX gate start in five BMX athletes of WC standard were investigated. The phases developed by the research and coaching team were somewhat similar to those outlined in research by Kalichová et al [45] and Zabala et al [14]. RT was shown to be the first and most variable phase (average *CV* 44% for M1[22], 42% for F1 as per Table 4-3). The variability in RT finding in Study 1 lead to considerable discussions with the CA BMX coaching and sports science staff. These discussions ultimately led to an application to the Australian Sports Commission for a grant to provide funding for a bespoke reaction timing device, and travel and accommodation to enable athletes to participate in a RT intervention study. This became Study 3 of the thesis.

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[22] Male participant #1 and female participant # 1

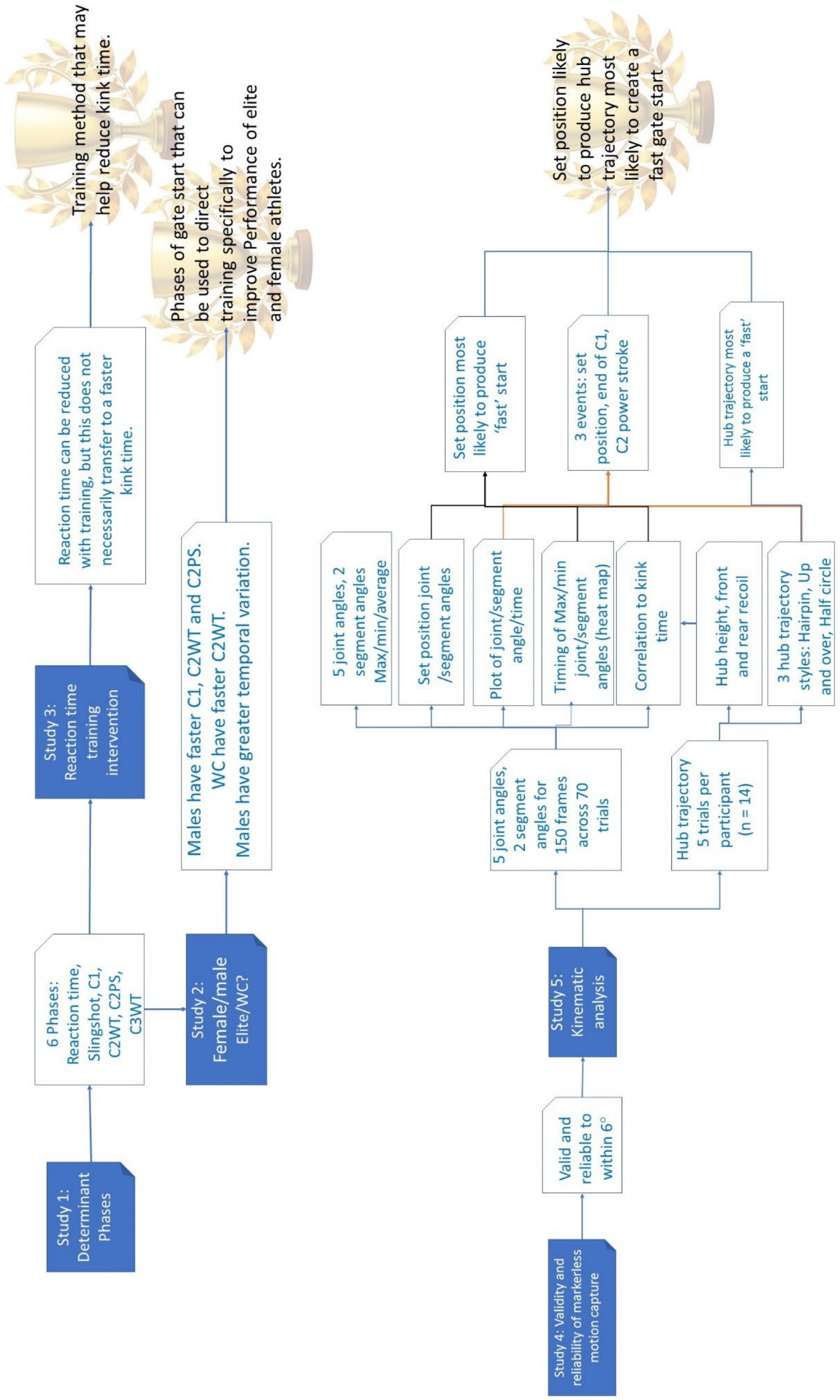

Figure 9-2 Overview of the studies and their interaction.

The phases identified in Study 1 were reaction time (RT), slingshot, crank 1 (C1), crank 2 weight transfer (C2WT), crank 2 power stroke (C2PS) and crank 3 weight transfer (C3WT). Most athletes had passed the kink by the end of C3WT. Disregarding the RT phase, the intra-athlete variation of the phases (3.4 -16.2%)[23] was low compared to that reported in other studies of locomotor tasks including walking gait and swimming [63, 140]. The inter-athlete correlation for the relative timing of these phases was also very high ($r > 0.9$)[24], thereby suggesting a high level of linear congruency [134]. The high level of inter-athlete correlation was further evidence to support the proposed definition and relative invariance of the phases described in this study. Such results imply that the five Olympic athletes spent a very similar percentage of time in each phase as each other – meaning that the relative temporal component of the action was invariant across the phases for all five athletes.

The quantification of sub-movement phase time can be used to determine the phase most likely to impact performance outcome [143]. In Study 1 performance outcome was described by kink time. The phases that correlated most strongly with kink time over the 50 trials for the entire group in Study 1 were C2WT ($r = 0.78$ $p = 0.01$, $R^2 = 0.61$) and C2PS ($r = 0.76$ $p = 0.01$, $R^2 = 0.57$)[25]. Such strong findings may suggest that a training focus on these two aspects of the gate start action may improve gate start performance. Despite a clear correlation between phases and kink time across the group data, only one athlete (F2) had a statistically significant correlation between any particular phase and kink time (RT $r = 0.79$ $p = 0.01$, $R^2 = 0.63$)[26] suggesting the importance of individualised testing and training.

The primary question from the coaches after Study 1 was “Is there a difference in how our Elite athletes move through the phases compared to the WC athletes?” If there is a distinct identifiable difference between WC and Elite

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[23] as per Table 4-3
[24] as per Table 4-4
[25] as per Table 4-5
[26] as per Table 4-5

athletes in phase duration, this could be targeted with training to improve competitive performance of Elite athletes. In the collection and processing the data for Study 1, data for Elite athletes were also recorded. This led to the development of Study 2, which was also expanded to investigate the potential difference between genders.

In Study 2, significant differences between the WC and Elite groups in phase timing and level of movement variation, and between males and females in both phase timing and level of movement variation were demonstrated. The findings from Study 2 suggested the ability to transfer from C1 to C2 is critical to performance because the C2WT phase had a longer absolute and relative time for the Elite than WC athletes. It was suggested by CA staff that this related to the position of the body at the end of C1. The body position at the end of C1 then became an important question to address in Study 5, where the athlete kinematics were analysed. The slingshot is a transition from the set position to the C1 position and as such may be influenced by the set position as certain set positions may require a more complex movement to the start of C1 than others. The potential to relate set position to slingshot phase time formulated a question for Study 5 which then reported set position kinematics.

One of the most important outcomes of Study 2 was the difference in genders. This had not been investigated before in known BMX research. The difference in overall race times is generally attributed to strength/power differences between males and females. Whether this is the primary cause of the difference in performance and what other factors may be contributors is unknown and would be very difficult to investigate with athletes of this level who have many years of experience. Since completion of this study, one of the BMX HPU female athletes has included more specific strength and power training for the shoulder girdle and arms into her regular gym program. A change in form on the gate has been observed by the researcher, but not quantitatively measured and cannot necessarily be attributed to strength gains alone.

Study 3 was conducted after the identification of the impact of the RT phase shown in Study 1. Technicians from the AIS built a bespoke timing device for

CA that could be used on and off the ramp to measure RT. The ability to operate this device in synch with the gate and independently meant that it was ideal for the intervention as well as for measurements on the gate. In keeping with the overall aim of this PhD to provide coaches and athletes with ecologically valid data and realistically repeatable methods, the intervention did not control for differences in time of day that training occurred, training conditions, surrounding distractions such as sound, other people, etc. and was varied in method, using a random mixture of visual and auditory stimuli. This variation in the environment in which the intervention occurred from day to day is a realistic representation of the life of a BMX athlete.

Study 3 was a two week training intervention that demonstrated a distinct difference in the change in performance of the control (n = 5) and intervention (n = 4) groups. The intervention group achieved a significant reduction in pedal and ramp RT which was consistent with literature when the intervention was specific to the mode of RT measurement [124, 146, 165]. The intervention tried to replicate the gate start action in a simplified standing mode, where the athlete straddled the bike and lifted the handlebars taking the front wheel off the reaction timer pedal in response to the stimulus. The stimulus was either a “set” call to prepare with a tone as the start, or a light sequence that replicated the start lights on the ramp. The different stimuli were used interchangeably during the intervention period with a random allocation each day for each athlete.

The lack of transfer to the kink time was in alignment with the findings of Papic et al [124] where the RT intervention training did not appear to transfer to the block time in the swim start. As per Papic et al [124] the results of Study 3 presented evidence that a simple intervention could be used to improve race start RT. While the results are only indicative and not definitive, there is enough evidence to warrant further investigation into this area, and to add such an intervention to an athlete’s regular training routine.

The importance of Study 4 lay in setting the foundation for Study 5 as it demonstrated the validity and reliability for the methodology proposed for use in Study 5. In keeping with the aim of the project to create ecologically valid results that could be understood and replicated by coaches and athletes, simple off-the-shelf action cameras and freeware software were selected.

The absolute error of the 2D markerless motion capture was 1.56 ± 0.92° across the 150 frames (1.2 s)[27]. The error was greatest in frames 50-100 (1.90 ± 1.12°) and least in the final 100-150 frames (1.33 ± 0.33°). These results suggested that the method developed was valid for use in assessing the BMX gate start and that the impact of the lens distortion at the periphery and parallax issues were minimal with this setup. The average error for each of the three phases remained under 2° which was considered acceptable in this context and when compared to the literature [88, 89, 180, 181].

The intra-tester reliability study of the 2D markerless motion capture demonstrated near perfect correlations [137] and an average AE remained under 6° for all measures[28], with the smallest variation being seen for the head and the largest being for the elbow; with a statistical power of 100% for all measures. The reliability of the temporal values was assessed by quantifying the frame at which maximum angles occurred, as this measure was required for Study 5. The reliability of the timing of max knee angle (R^2 = 1.0, ICC = 0.98)[29] was near perfect across all measures, with the time to the min shoulder angle showing the lowest correlation of all (R^2 = 0.23, ICC = 0.43 as per Table 7-2), possibly because of abduction. The overall high intra-tester correlation for each of these timings across all joints/segments with the exception of the shoulder was considered adequate for this purpose [137]. It would be interesting to repeat the study having done all of the video analysis for Study 5. The researcher noted a significant learning effect during the PhD project and would anticipate that the intra-tester reliability would have improved when analysing the data in Study 5.

Study 5 was the capstone study of the PhD research program. As with previous studies in the PhD research program, the ‘audience’ was the coaches and

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[27] as per Table 7-1

[28] as per Table 7-2

[29] as per Table 7-2

athletes. The question came from CA BMX Head Coach Wade Bootes “What does fast look like?” It is hoped that Mr Bootes can take this research and use it to help format his training in order to prepare athletes for the 2020 Tokyo Olympics.

The results of Study 5 demonstrated that the athletes with the *back* set position and *hairpin* trajectory were faster than the other set positions and trajectories. As is noted in the Discussion of Study 5[30], the COM travels in a relatively straight line through the slingshot, C1 and C2WT phases. At the end of C1, the athlete is positioned such that they are able to bring the second leg through for the weight transfer ready for the second crank. Thus, the results of Study 5 together with those of Study 2, suggested that one of the key aspects associated with a fast WC gate start is the *back* set position which enables a faster transfer from C1 to C2, that is the C2WT phase.

The role of the research in Study 5 was to provide coaches with more tools for designing training protocols to improve gate start performance. The concept of training to increase recoil is an interesting counter-intuitive take on training for a fast gate, although such a movement is an example of a stretch-shorten cycle. Recoil presents an easily measurable parameter that is easily understood by coaches. In discussion with coach Jake Stephenitch of Spark BMX, this concept not only makes sense but fits with current thinking in BMX training worldwide (Jake Stephenitch, personal communication, 18 October, 2018). A skill acquisition intervention study based on the concept of increasing recoil to decrease kink time could be undertaken with an athlete of nearly any level on a ramp of any height, even via the use of a portable training ramp.

ROMs reported in Study 5 can be used to inform resistance training and rehabilitative exercise prescription. The ROMs and frame at which maximum and minimum joint angle occurred can be used to generate average angular velocity which together with the ROMs would be used for exercise prescription. This information would help not only in the selection of the most specific

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[30] §8.6

activities but also the optimal velocity of these exercises to approximate the BMX SX gate start action for off track training. There currently appear to be few strength and conditioning coaches with a BMX racing specialist interest, however this area of off track training is growing with the understanding of the importance of power development for performance outcome and perhaps for decreasing injury risk [12, 145, 147, 193].

9.3 Limitations

The ecological validity of this PhD project is both its strength and weakness. The measurement error involved in visual judgement of movement in Studies 1 and 2 and in markerless motion capture in Studies 4 and 5 mean that results must include an allowance for this larger than ideal error. An attempt to account for this involved, where possible by reporting $p < 0.01$ as well as $p < 0.05$ in statistical analysis.

A greater number of athletes and trials would strengthen all five studies. A number of issues limited the athletes involved, including the availability of athletes at a WC level, the number of SX tracks in Australia, daylight time at Sleeman SX track and financial resources for cameras, track hire and travel. Because access to DA athletes was limited after 2015 for political reasons within BMXA and CA, the athletes available to the researcher were WC, of which Australia only had a maximum of five athletes at any time during this time period. A larger number of participants would have extended the results of Studies 1, 2, 3 and 5, allowing a greater understanding in the difference in movement characteristics between WC and Elite athletes and between the genders. A greater number of trials would have strengthened Studies 1, 2 and 5 by increasing the volume of data for each participant. The number of trials was limited by the number of trials each athlete did in front of the left side camera in daylight hours during a training camp.

No statistical difference in kink time was found between days on a training camp, but between camps it was possible for changes in action to occur that could create significant movement changes, such as an injury or a development in strength or alteration of technique. While some athletes performed more than ten trials (Studies 1 and 2) or five trials (Study 5) in front of the left camera, many did not, meaning that the lowest number of trials done by an athlete that would give meaningful results was selected. Where more than that number of trials was recorded for an athlete, the best (i.e. lowest kink time) were taken. Study 3 (the RT intervention) was an exception with the number of trials per athlete prescribed.

It was considered important to minimise interference with the training camp program in Study 3 to minimise the “white coat” effect. This also helped to maintain goodwill with the coaches and BMX CA staff and athletes as their training programs were not interrupted by the research activities.

While limitations are acknowledged, the number of athletes and trials per athlete assessed for this PhD project were substantially greater than that reported in previous literature. For example, Gianikellis et al [38] reported displacement, velocity, knee ROM and torso ROM for one trial for each of three participants on a non-standard ramp. Kalichová et al [45] reported velocity (head, wrist, elbow, shoulder, knee and ankle), time splits, joint angles (elbow, shoulder, hip and knee) for one trial for each of two participants. The most recent published study reported time splits, bike velocity, power and torque averages for five trials for each of 12 participants [16]. Summary plots of knee and hip joint angles against time were also presented in Study 5[31]. This indicates the major contribution of this PhD to the field.

There are acknowledged limitations when measuring the movement of complex joints such as the shoulder and hip with a 2D system when they are free to move in all three planes. Other researchers have attempted to attempted frontal plane movement measurement but have not reported it [16, 45] thus as yet there is no published understanding of this movement in BMX. This is a valu able area for further research, particularly examining how the arrangement of handlebar may influence performance given that the width of grips and sweep[32] of the bar is variable.

The technology available at the start of this project (2014)[33] was limited compared to that now available at the end of the PhD term. New technologies such as IMU units have become much more accessible in the last few years.

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[31] Appendix 8

[32] BMX handlebars are not always straight but can be a curved arc, or angle the grips back toward the body, thereby changing the degree of rotation from shoulder to handgrip.

[33] This thesis was undertaken on a part time basis

There is still much work to be done in the development of data processing to make these units easy to use for coaches and athletes, but the potential is great in terms of field research in sports biomechanics. The research team also experimented with instrumented cranks for force and power measurement, however these are currently limited in terms of function for BMX athletes. Most power meters have been developed for road cycling and have a low sampling rate. Others used in track sprinting require a closed radio loop setup for data transfer. The ability to sample at a high rate and store the data locally was important for research in BMX racing because of the high cadence used and the distance traversed. Cranks such as the SRM Powermeter (Schoberer Rad Messtechnik, Germany) which have been used in BMX power studies [31, 44] activate after the first 1-2 s of movement, meaning that the BMX gate start action may be completely missed. Dr Haakonssen and Mr Bootes of CA both had experience with these units and recommended that they not be used for this project. A Verve Infocrank (©Verve Cycling, UK) was also trialled by the researcher but found to be unsuitable because of the low sampling rate. Power measurement systems need to be robust in an electronically noisy environment to be effective at a BMX track to avoid radio/wifi/Bluetooth interference and crossover, survive the high impact crashes possible in BMX and collect data at a high sampling rate for at least 30 s. Devices such as the loadsol ® (Datenschutz, Germany), DI-1000 Wireless WiFi Load Cell Interface (Loadstar ™ Sensors, USA), or the miniature load cell converter by I.M.S. (I.M.S, Israel) could be adapted and applied to the handlebars and pedals or shoes to measure applied force.

The RT training intervention study could have benefitted from having a longer and more structured intervention. A similar study in swimming used a four week intervention, with the intervention group performing 10.6 ± 2.1 sessions, (n = 5) which is fewer than the number of sessions each of the four participants undertook in Study 3 [124]. The length of the study was limited by the availability of the athletes who attended the BMX training camp. Different RT training formats were used during the intervention training sessions, including a mix of auditory and visual stimuli, however, the reaction required for all stimuli methods was the same, i.e. lifting the front wheel off the RT pedal. While the strength of this methodology is that it was easy to perform and realistic in terms of the training environment, a more consistent format that more closely matched the gate start style of the athlete may have had a greater effect. For example, some athletes prefer to watch the lights and respond to the visual stimulus. Such athletes may have seen a greater improvement on the track with a purely visual stimulus training routine.

All studies were restricted to a limited capture space. The maximum distance travelled by the athlete and bike through the 150 frames was 3.1 m in the horizontal plane and 1.2 m in the vertical plane. This took the athlete and bike to the edge of the camera's field of view. This limitation is noted as beyond the centre third capture area, parallax errors need to be considered. The GoPro Hero 4 Silver camera is an action camera and if used on the wide setting the effect of the fisheye lens distorts the image, so the 'normal' setting was used. Nevertheless, the validity results reported in Study 4 indicated that any distortion due to lens curvature was not a significant concern, with the degree of inaccuracy not exceeding 2° [129].

The findings presented in Study 5 were novel in terms of its presentation of data formats in sports kinematic studies. The three events (set position, end of C1 and C2 power stroke), set position styles (*back, upright* and *angled*) and hub trajectory shapes (*hairpin, half circle* and *up and over*) were qualitatively rather than quantitatively defined. This meant there was a degree of subjectivity in this categorisation. The researcher has tried to negate any bias by a) conversation with CA BMX coaches and staff, b) conversation with international coaches and c) reviewing blogs and training videos put online by WC athletes and coaches. Further research with a greater number of Elite and WC athletes may enable further quantification and refinement of these parameters. In the meantime, findings presented in Study 5 present a starting point for further examination of ways to describe and improve BMX gate start performance.

9.4 Areas of further research

As can be seen in the deterministic models presented in section 1.7 at the beginning of this document there are many contributing components to the achieving a successful BMX gate start. Figure 9-3 is a reviewed version of the deterministic model presented in Chapter 1 with the areas examined in this thesis shaded yellow. The research presented in this thesis is limited to the manipulation of one aspect of reaction time, and externally observable components of the development of power, that is, the movement development as measured with kinematics. As can be seen, there are many areas yet to be investigated, such as the development of torque.

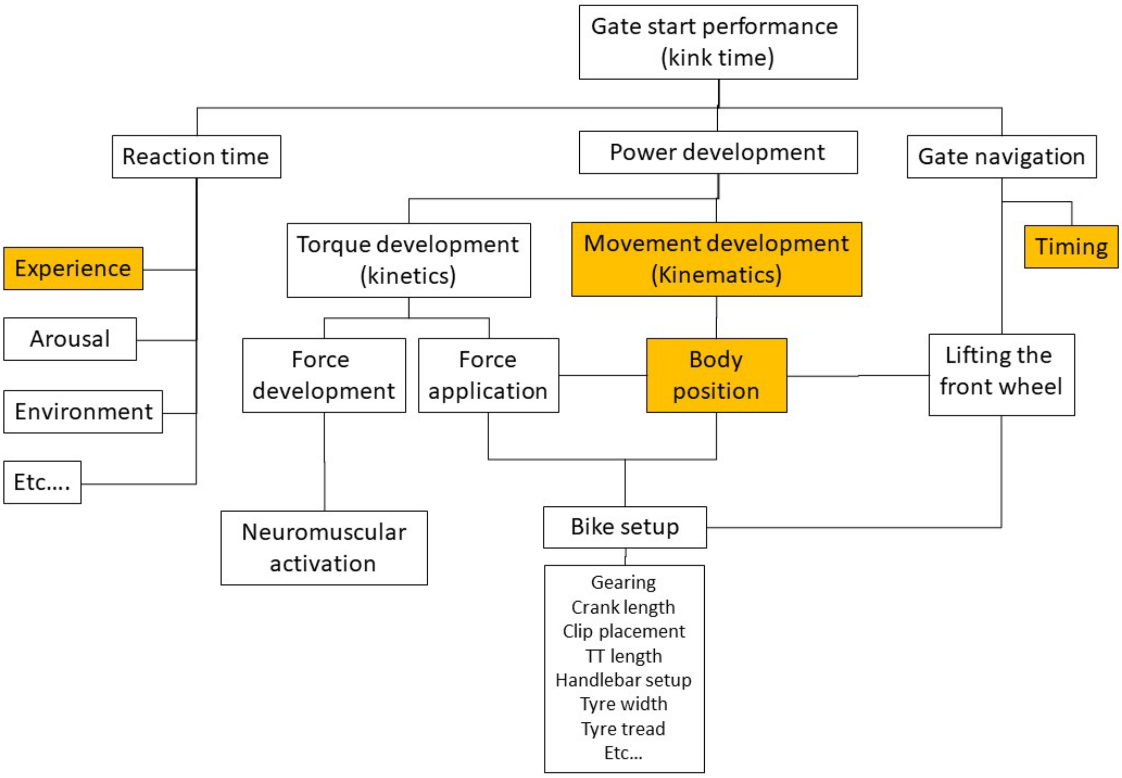

Figure 9-3 Updated deterministic model showing the areas investigated in this thesis in yellow.

Study 1 and 2 presented information regarding the phases of the BMX SX gate start action. Further research could provide additional insight into common phase durations and the typical degree of variation for different classes of athletes, such as under 16, masters, etc. This could be used for training purposes to prepare athletes for competition by identifying areas for improvement for each athlete. Skill acquisition and strength and conditioning intervention studies based on these findings may provide more insight into whether these approaches can change an athlete's relative phase duration, if this positively impacts kink time and if such changes are greater than the normally expected inter-trial variation.

Study 3 was an important motor control study in that it showed the potential trainability of RT, however post-training retention was not investigated and there was no clear transfer to the kink time. A study into the duration of training retention may demonstrate the training period necessary to allow a permanent change. The question of transfer to kink time is difficult to manage because of movement variability. If the RT decreases by 10 ms and if everything else remained the same, it could be anticipated that this would be reflected in a decrease of 10 ms in kink time, however this was not the case. Which phase/phases 'absorbed' the 10 ms throughout the gate start action is not as yet clear. Because of the very small changes in RT relative to the total gate start time, a large number of trials may be necessary to show statistically significant change. It was also postulated that some athletes may be near their RT threshold, that is, their RT is almost as low as it can be. The minimum possible RT to auditory stimulus has been thought to be 100 ms [117], however muscular response has been seen at 60 ms [122] suggesting that this may be an overestimation, especially in athletic populations. Exactly what the threshold may be and if there is a difference based on gender, training or genetics requires further investigation.

As can be seen in Figure 9-3, body position is critical for power development and gate navigation, two of the key determinates of the gate start performance. The investigation into the kinematics of the BMX gate start as reported in Study 5 will hopefully be repeated with IMU technology in the near future. The 3D reporting that IMU technology affords will provide valuable insight into several questions, such as what degree of non-sagittal plane movements such as rotation, abduction and adduction of the hip, torso and shoulder occur during the BMX gate start and how these movements may influence performance. Because of the ease in setup of IMUs and their ability to maintain a high degree of ecological validity compared to a marker based 3D motion capture format, it is hoped that a greater number of BMX athletes of varying proficiency and gender will be analysed with IMUs to give a broader picture of what constitutes a ‘fast’ gate start.

As yet, the identification of the centre of mass (CM) of a BMX rider wearing helmet and race kit has not been published. An accurate representation of the CM would then enable a study of the relative location of the CM relative to the points of application of force, the handlebars and pedals which would begin to answer some of the ‘cause and effect’ questions around the impact of the set position, recoil distance and maximum hub height. Using force transducers that can store data locally in the pedals or shoes, and in the handlebars would also enable study of the application of force. This would enhance our understanding of the balance of force application between the hands and feet, as well as the left and right sides of the body. Such information would be useful for coaches and athletes in fine tuning movement and muscle activation to optimise the gate start action.

An intervention study based on the findings of Study 5 may determine the effect of how changing a gate start style from *upright* to *back* impacts the kink time. A case study with an Elite athlete working with an experienced coach could provide a foundation for such a research question. Such a study could investigate the use of different forms of knowledge of performance such as video feedback, to facilitate a change in set position. Pre-post analysis of kink time could be used to determine the efficacy of the intervention. Such a study could initially be carried out during a short term training camp and if positive trends occur could be extended over a longer period. Such research should also utilise retention and transfers tests performed at multiple time-points to assess the time-course of these potential changes from a longer duration intervention.

Chapter 10: Conclusion

10.Conclusion

This PhD project presents an ecologically valid and ‘coach and athlete friendly’ analysis of the biomechanics of the BMX SX gat start. Key findings were:

- The overall complex action can be divided into 6 determinant phases.
- The crank 2 weight transfer phase is the one most likely to impact kink time in five WC athletes.
- Female athletes have a different temporal action to male athletes.
- RT can be improved with off track training, but this may not transfer to an improvement in kink time after two weeks of training.
- There are 3 common set positions and 3 common hub trajectory shapes used by Elite and WC athletes.
- The *back* set position is most likely to produce the *hairpin* hub trajectory which describes the action of the fastest WC Australian BMX SX athletes.
- WC athletes have a faster crank 2 weight transfer phase, possibly because they assume the *back* set position.

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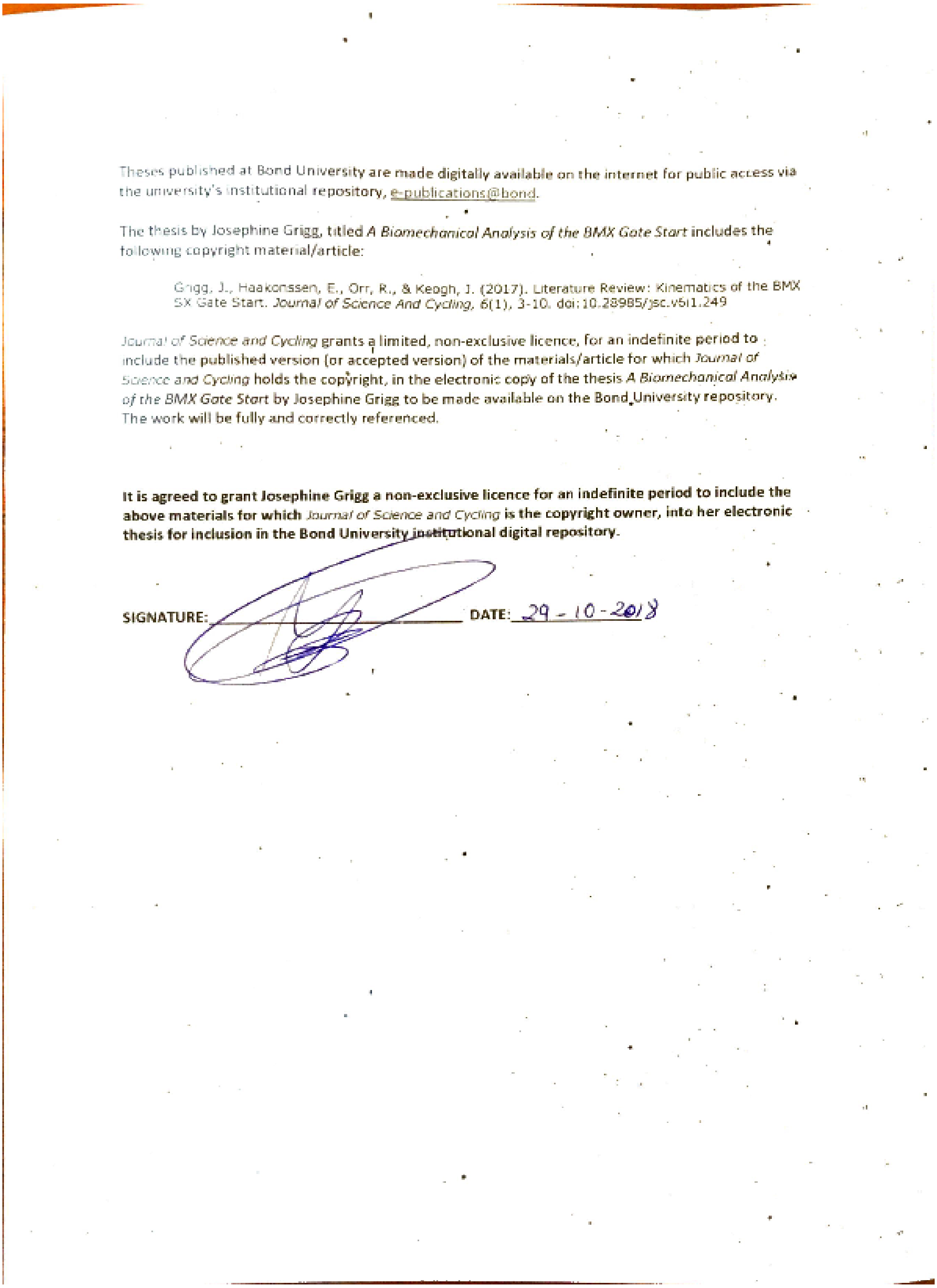

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SIGNATURE: Rodrigo Rico Bini DATE: 3rd of December 2018

14.Appendix 3: Permission to reprint from Routledge, Taylor & Francis

Tue 9/10/2018 8:36 PM (EMAIL)
Dear Josephine (if I may),

Many thanks for your query with Sports Biomechanics' Editor-in-Chief, Daniel Fong, who has kindly passed this on to me as I'm the journal's Managing Editor here at Routledge, Taylor & Francis.

I include some Author, Article Reuse Guides for your convenience. Please see page 9, with the information as per below. You won't need to request permission through our Rightslink, or email our Permissions team, so all is fine. However we don't tend to sign letter.

Can I include my article in my dissertation?

If you are lucky enough to publish a journal article before you are awarded your PhD, yes, you can include your article in your dissertation. If the dissertation is to be published online or in a repository by your institution, please note that you cannot include the final, typeset version and should instead use the Accepted Manuscript (AM) version. You do not need to request permission for this reuse, but you should ensure that you are including a full citation to the journal as the original source of publication.

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I imagine the reference to *The Journal of Nursing Home Research* is a mistake and should be *Sports Biomechanics*.
With best wishes,

Alejandra.

Leach-Nunez, Alejandra Alejandra.Leach-Nunez@tandf.co.uk

15. Appendix 4: The UCI standard BMX SX gate procedure

From Union Cycliste Internationale, *Part 6 BMX*, in *UCI Cycling Regulations*. 2014, Union Cycliste Internationale: Aigle, page 86

The Start

6.1.042 All riders must start in their designated gate positions. The penalty for starting from any other gate position is disqualification (DSQ).

It is each rider's responsibility to be in the staging area and on the gate in the correct gate position at the appropriate times. If the rider is not on time for staging as indicated by the staging officials, the rider will lose the gate pick position and must choose the gate last.

In case of a re-run, all riders must start in the same gate position as previously designated.

Any rider who in any way interferes or attempts to delay or interfere with the start procedure of a heat for a reason not accepted by the president of the commissaires' panel may be disqualified (DSQ).

6.1.043 A BMX heat or run shall be started using a starting gate equipped with a voice box starting system.

Where an electronically controlled starting gate in combination with a voice box supported starting system is used, the recorded commands of the voice box (the “starter's call” shall be as follows:

a. Stage 1: «ok riders, random start».

b. Stage 2: «Riders ready». «Watch the gate».

For safety reasons, the stop button can be pressed at any time, up to the end of Stage 2.

The requirements for a voice box and an electronic starting system shall be as described in Annex 3.

Bike Position on the Start Gate

6.1.044 The front wheel must be placed against the gate, be grounded and remain stationary during the starter's call as defined in article 6.1.043.

16.Appendix 5: Informed consent form RO1913

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ABN 88 010 694 121
CRICOS CODE 00017B

EXPLANATORY STATEMENT

BUHREC Protocol Number: RO1913

STUDY TITLE: Biomechanics of the BMX gate start

PRINCIPLE INVESTIGATORS:

Dr Justin Keogh
Bond University
07 5595 4487

Josie Grigg
Bond University
0403193815

Dr Eric Haakonssen
BMX Australia

Who is doing the study?

Josie Grigg is doing research under the supervision of Dr Justin Keogh (Associate Professor) in the Faculty of Health Science towards a PhD at Bond University.

Dr Eric Haakonssen is the senior physiologist with BMX Australia. He has a supervisory role in the research.

Gate start technique is critical to success in BMX (bicycle motor cross) racing. Researchers from Bond University are conducting this study to evaluate the difference in biomechanics (body movement patterns) and muscle activation (which muscles are fired, how much and when) of the first three pedal cranks of a BMX gate start and how this may differ between elite and sub-elite riders. The results from the study will be used by the coaching staff and strength and conditioning staff of each team to improve rider development.

BMX Australia, AIS and Bond University in Partnership

BMX Australia coach Wade Bootes will initiate the recruitment of the athletes. AIS and BMX Australia employee and senior physiologist Eric Haakonssen (as well as Bond University's Josie Grigg if required) will assist in the recruitment process by further explaining the project to the athletes and guardians where applicable. Data analysis and reporting will be completed by Josie Grigg at Bond University under the supervision of Dr Justin Keogh. Participation in the study is voluntary and not a training requirement.

Why are we doing the study?

Currently there is limited understanding in what defines a good gate start technique. This study will help understand this by investigating the movement patterns of high performance BMX Australia riders. Riders in the sub-elite program, that is the next category down, will then be analysed. The differences in the body movement and muscle usage may help coaches direct training patterns to enable the sub-elite riders to develop a winning gate start technique.

Your involvement in the study

If you choose to participate in the study, you will be asked to attend a gate start practice session at the Sleeman BMX Supercross Track. This will be attended by senior coaching and support staff from BMX Australia. You will be fitted with a wireless EMG (electromyography i.e. muscle activation measurement) device on your arm, back, buttock, leg and shoulder. An accelerometer, which is like a plastic match box, will be fitted to your back on the base of the neck, and on your back just underneath your belt. All of these devices are safe and non-invasive. Privacy will be insured as the devices are being fitted.

You will then perform a standard BMX gate start as if you were starting a race. This will be videoed. This will be done 5 times, and you can have a break between each one for up to 20 minutes. The whole data collection process will take 2 hours maximum including rest periods.

Your rights during the study

Your participation in the study is entirely voluntary. You are not expected to participate and you may withdraw your consent to participate freely, without prejudice and without any consequence at any time.

Risks associated with participating

The risks involved are no greater than in a normal gate start training session.

Benefits of participating in the study

By participating in this study, you will receive potentially valuable information about your gate start technique. If you are not currently part of the BMX Australia High Performance Program (HPP), your coach will receive an analysis that describes how your gate start technique differs from that of the HPP team with some recommendations on what you may consider changing in your technique.

Who gets the results?

If you wish to have a copy of your personal results, we are happy to send a report and detailed explanation to you. BMX Australia HPP coaching staff will receive a summary of all results, as well as individual breakdown of technique where requested.

All results are confidential

All of your personal information and results will be kept completely confidential. Your results will only be viewed by the appropriate researchers and BMX Australia HPP coaching staff. When your results are produced, no names will be identified in any case. Researchers will retain individual study participants' identification and results will be held on a password protected computer and no information will be disclosed to third parties without your consent.

Questions/further information

If you have any further questions regarding any part of this study, please feel free to contact the chief investigator of the study, Dr Justin Keogh from the Faculty of Health Sciences and Medicine on 5595 4487 or any of the other researchers listed on page 1.

Principle Researcher: Dr Justin Keogh **Signature:**

Co-Researcher: Josie Grigg **Signature:**

Should you have any complaints concerning the manner in which this research is being conducted, please do not hesitate to contact Bond University Research Ethics Committee:

Bond University Human Research Ethics Committee,
c/o Bond University Office of Research Services.
Bond University, Gold Coast, 4229

Tel: +61 7 5595 4194 Fax: +61 7 5595 1120 Email: buhrec@bond.edu.au

Participant Informed Consent Form

Project Title: Biomechanics of BMX Gate Start

Project Number: RO 1913

I agree to take part in the above Bond University research project. I have read the Explanatory Statement. I am willing to:

- be fitted with EMG (electromyography) and accelerometry devices
- be videotaped performing a BMX gate start
- complete a BMX gate start on the Sleeman BMX Supercross ramp
- make myself available for a retest should that be required

I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party.

I also understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw freely at any stage of the project.

Please tick the appropriate item:

___ The information I provide can be used by other researchers as long as my name and contact information is removed before it is given to them

___ The information I provide cannot be used by other researchers without asking me first

___ The information I provide cannot be used except for this project

Name:.. (please print)

Signature:..

Date:............................

Under 18 Parental/Guardian Informed Consent Form

Project Title: Biomechanics of BMX Gate Start
Project Number: RO 1913

I agree that ....(full name of participant) may take part in the above Bond University research project. I have read the Explanatory Statement, which I keep for my records.

I am willing to allow ………………………………………… to:

- be fitted with EMG (electromyography) and accelerometry devices
- be videotaped performing a BMX gate start
- complete a BMX gate start on the Sleeman BMX Supercross ramp
- make myself available for a retest should that be required

I understand that ……………………information will be kept secure and no names will be used in any publication or presentation to protect ………………………….'s identity from being made public.

I also understand that ……………………..'s participation is voluntary, that s/he can choose not to participate in part or all of the project, and that s/he or I can withdraw freely at any stage of the project.

I agree that other researchers may use the information provided in this study as long as the participant's name and contact information is removed before it is given to the other researchers

Participant's Name:______________________
Participant's Age:_________
Parent's/Guardian's Name:___________________
Your relationship to participant:________________
Signature:__________________________ Date:_____/_______/________

17. Appendix 6: Informed consent form 16165

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(from overseas)

Email: hsm@bond.edu.au

ABN 88 010 694 121
CRICOS CODE 00017B

EXPLANATORY STATEMENT

Participant Informed Consent Form

Project Title: BMX Reaction time training
Project Number: 16165

I agree to take part in the above Bond University research project. I have read the Explanatory Statement. During the two week study, I am willing to:

- be videotaped performing a BMX gate start
- complete a BMX gate start on the Sleeman BMX Supercross ramp
- be available for a retest should that be required
- participate in three track sessions a week with a focus on the gate start, 2-3 gym sessions and 2-3 sprint sessions a week
- perform a sensory-reaction time exercise up to 15min each day

I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party.
I also understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw freely at any stage of the project.

I understand that de-identified data from this research may be made available to other researchers as long as my name and contact information is removed before it is given to the other researchers

Name:.. (please print)

Signature:...

Date:............................

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Email: hsm@bond.edu.au

ABN 88 010 694 121
CRICOS CODE 00017B

EXPLANATORY STATEMENT

Participant Informed Consent Form

Project Title: BMX Reaction time training
Project Number:

I agree to take part in the above Bond University research project.

I have read the Explanatory Statement. I am willing to:

- be videotaped performing a BMX gate start
- complete a BMX gate start on the Sleeman BMX Supercross ramp
- be available for a retest should that be required
- participate in three track sessions a week with a focus on the gate start, 2-3 gym sessions and 2-3 sprint sessions a week
- perform a sensory-reaction time exercise up to 15min each day

I understand that ……………………information will be kept secure and no names will be used in any publication or presentation to protect …….……………………’s identity from being made public.

I also understand that ……………………’s participation is voluntary, that s/he can choose not to participate in part or all of the project, and that s/he or I can withdraw freely at any stage of the project.

I agree that other researchers may use the information provided in this study as long as the participant’s name and contact information is removed before it is given to the other researchers

Participant’s Name: ______________________ Participant’s Age:_________

Participant’s Signature: ____

Parent’s/Guardian’s Name: __________________

Relationship to participant: ________________ Date:_____/_______/________

Signature: ____

18. Appendix 7: Video footage collection preparation and procedure

This study will be done by simply recording competition style gate starts that are part of the practice session, including those done as part of the mock competition days. It is currently anticipated that no extra gate starts beyond those programmed into the training schedule will be required.

Between ‘starts’ the testers will stop the cameras, check batteries and memory capacities, and then restart the cameras. They can then stand out of the way during the race. They will record the subject number and secondary identifiers of the competitors closest to the cameras (1 on each side) and then work out which trial it is for that competitor to ensure that we have enough of each competitor.

We are aiming to record 5 trials for at least 15 riders during this study.

❗ It is imperative that consent forms are signed before the video recording which includes parental consent for those under 18 at the time of testing.

Setup Requirements:

Permission slips signed – including parental permission where that is relevant.
Schedule to testers
Access to ramp 10 minutes hour before riders to set up cameras.
Somewhere safe to stand that is out of the way
Cameras firmly attached to both sides of the ramp.
The ability to access the cameras between trials

Video Only Subject Requirements: (time requirement 5 minutes max)

Some secondary identifier e.g. colour of clothing, colour of bike
Measurement of bike frame to scale video information
At least 5 trials recorded (tester will notify once this is complete)
Record gearing, tyre and crank information, and record (with timestamp) if altered.

19.Appendix 8: Participant kinematic results

Participant 1 Back, Hairpin

Figure Appendix 8 - 1 Participant 1 set position

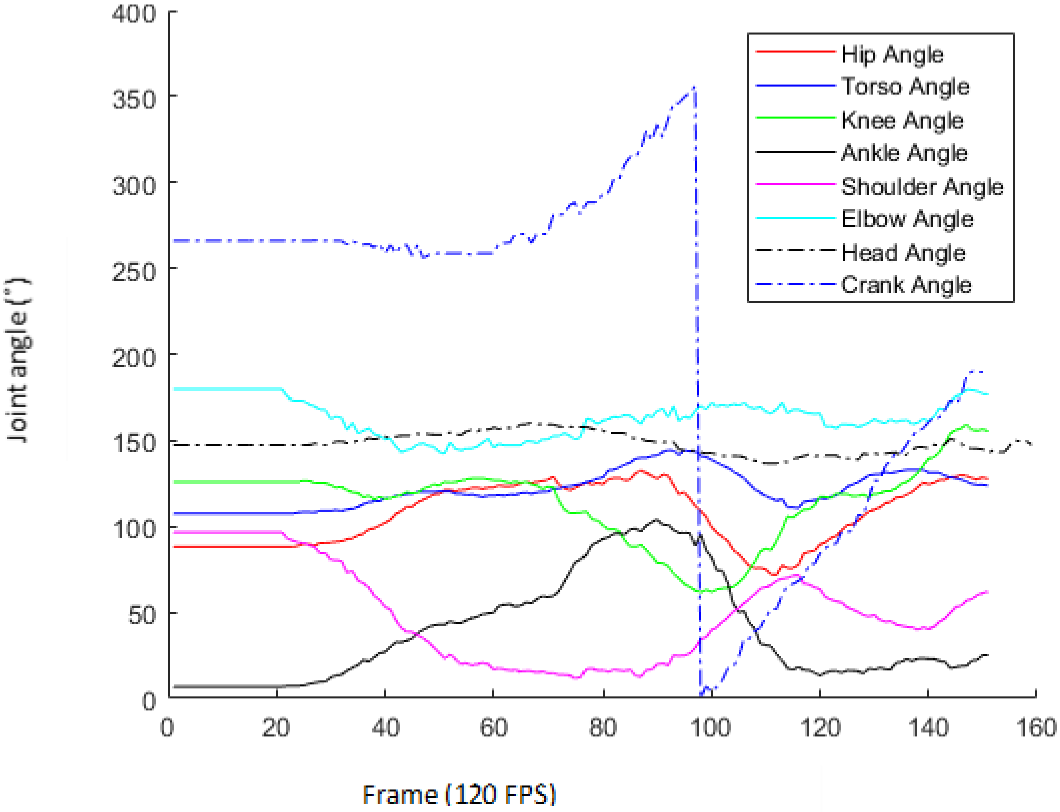

Figure Appendix 8 -2 Participant 1 kinematics profile plot example

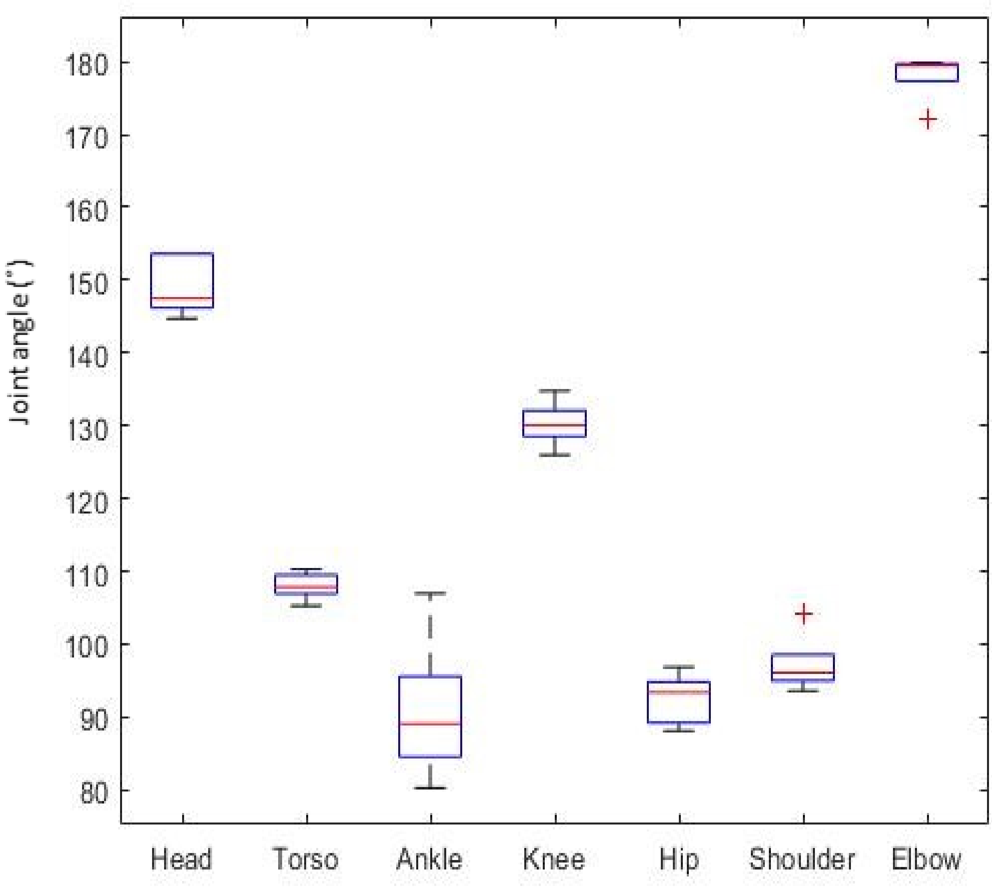

Figure Appendix 8 -3 Participant 1 set position joint angles box pot

Table Appendix 8 - 1 Participant 1 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.222	92	1	147	98	90	1	1	75	1	51	87	112
2	1.231	97	19	146	102	146	21	30	92	19	51	145	111
3	1.232	100	1	146	101	150	18	30	59	1	51	146	108
4	1.234	99	18	151	103	151	18	27	75	1	48	69	113
5	1.253	133	1	149	103	150	21	30	89	1	68	142	110
Av	1.234	104	8	148	101	137	16	24	78	5	54	118	111

Participant 2 Back Up and Over

Figure Appendix 8 - 4 Participant 2 set position

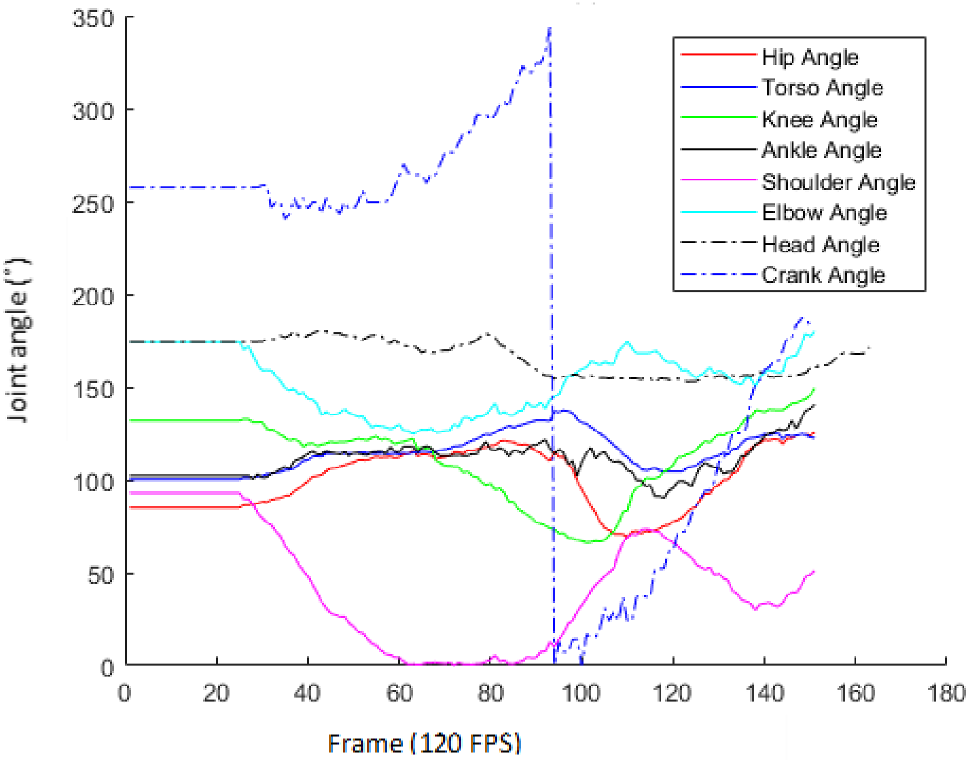

Figure Appendix 8 -5 Participant 2 kinematics profile plot example

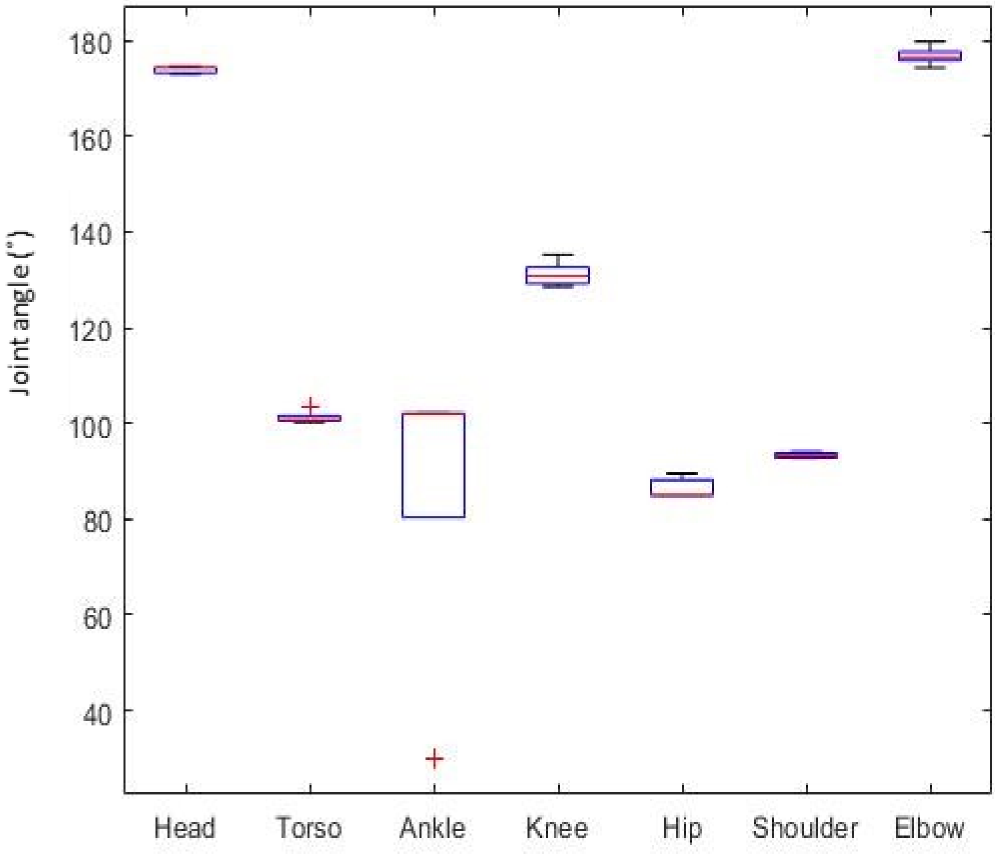

Figure Appendix 8 - 6 Participant 2 set position joint angle boxplot

Table Appendix 8 – 2 Participant 2 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.229	96	1	151	101	151	1	114	59	1	69	151	111
2	1.236	96	1	151	101	151	1	118	72	1	63	151	110
3	1.239	94	1	150	99	95	1	123	81	1	65	150	112
4	1.252	100	1	151	102	151	1	118	91	1	69	150	114
5	1.277	100	1	151	104	151	1	127	92	1	72	150	117
Av	1.247	97	1	151	101	140	1	120	79	1	68	150	113

Participant 3 Angled Half circle

Figure Appendix 8 - 7 Participant 3 set position

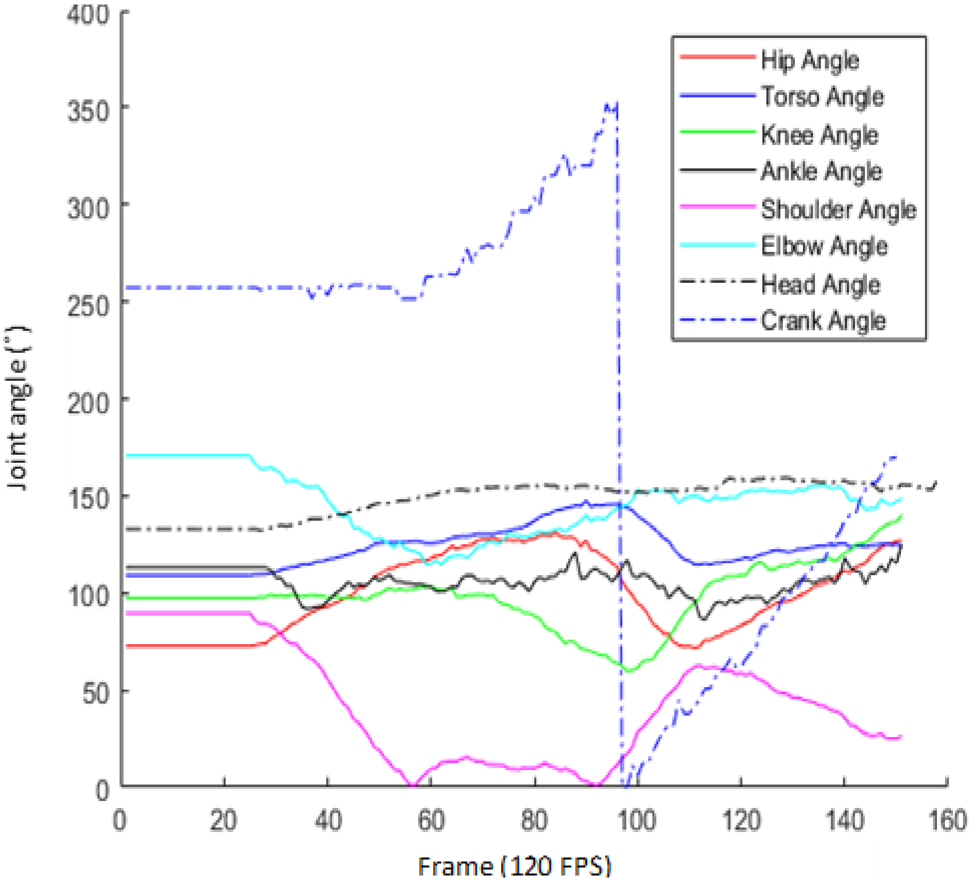

Figure Appendix 8 - 8 Participant 3 kinematic profile plot example

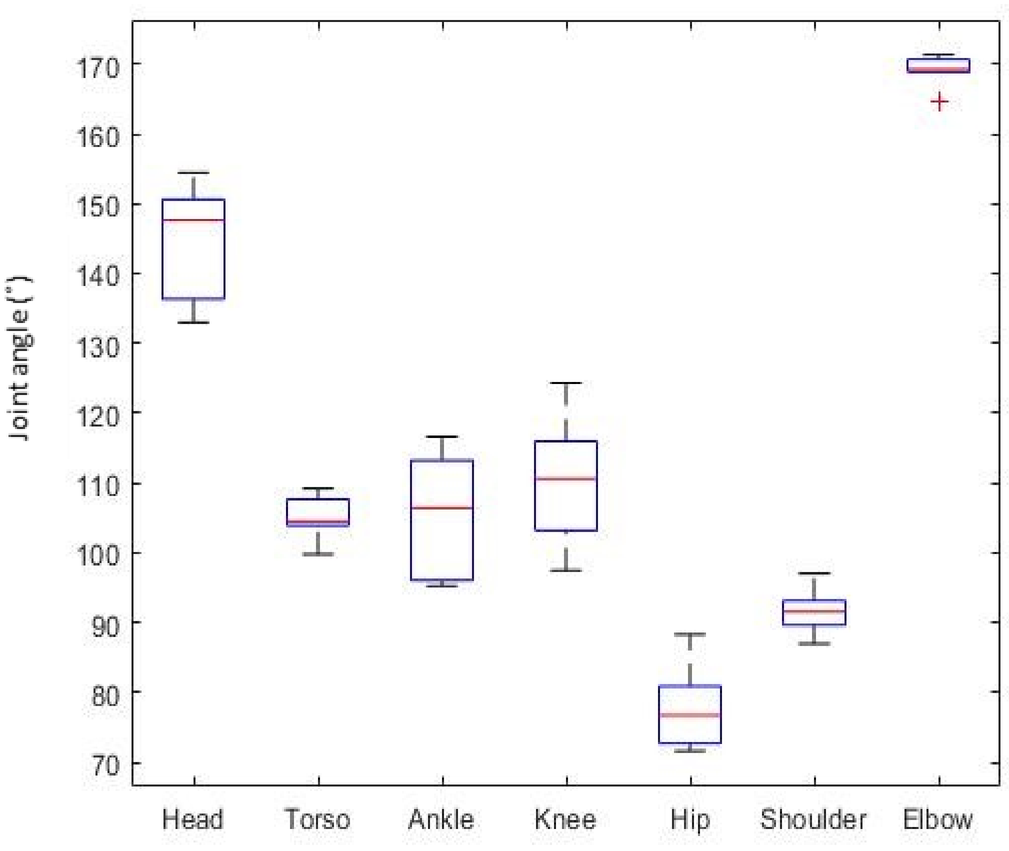

Figure Appendix 8 - 9 Participant 3 set position joint angle box plot

Table Appendix 8 - 3 Participant 3 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.294	89	20	149	92	151	13	114	90	13	85	77	4
2	1.311	88	1	151	99	151	1	117	56	1	63	79	1
3	1.313	92	1	151	94	147	1	113	72	21	149	64	109
4	1.327	90	1	151	98	151	1	113	92	1	62	84	111
5	1.329	95	1	151	96	151	1	36	66	101	53	150	110
Av	1.315	91	5	151	96	150	3	99	75	27	82	91	67

Participant 4 Upright Hairpin

Figure Appendix 8 - 10 Participant 4 set position

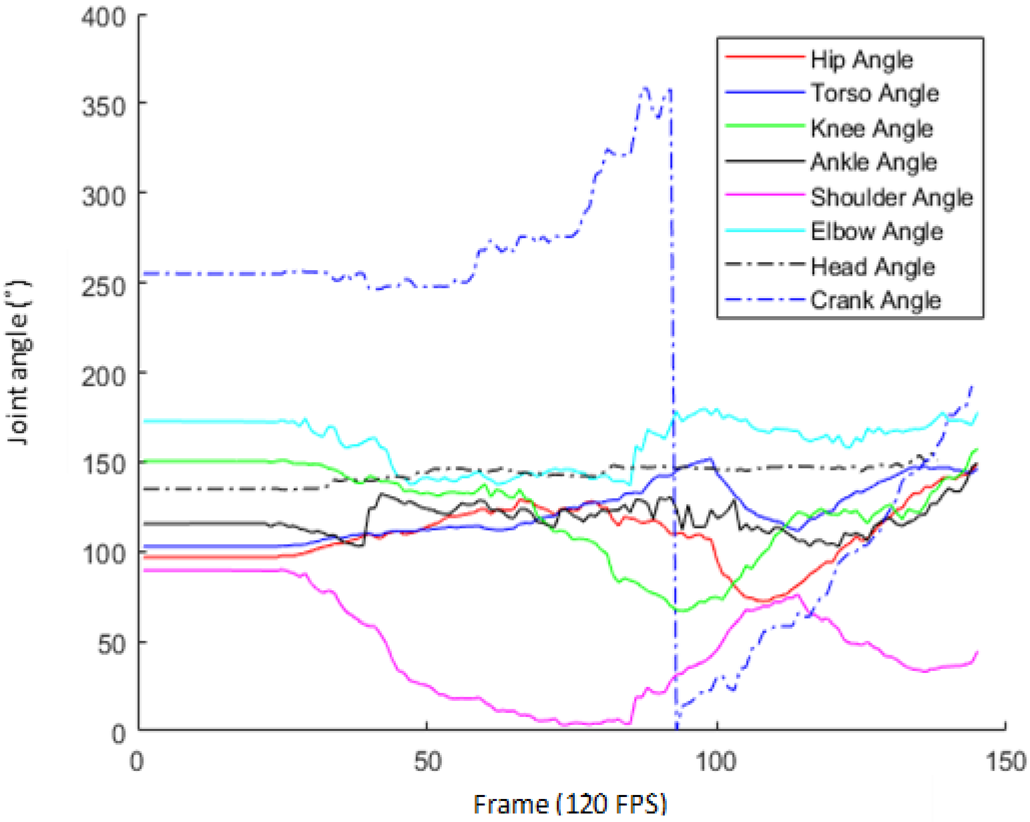

Figure Appendix 8 - 11 Participant 4 kinematics profile plot example

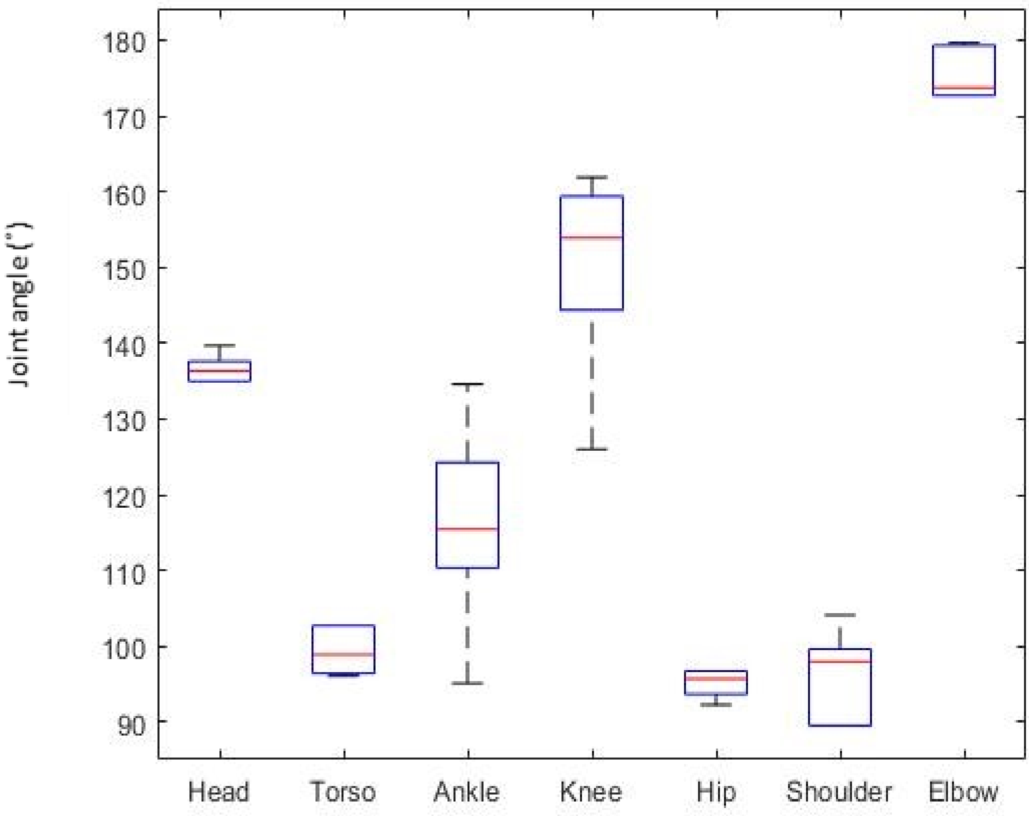

Figure Appendix 8 - 12 Participant 4 set position joint angles box plot

Table Appendix 8 - 4 Participant 4 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.222	91	1	150	97	141	1	127	88	96	52	139	109
2	1.232	99	6	145	94	145	25	121	74	100	85	145	108
3	1.249	99	19	146	98	151	1	126	78	97	78	145	104
4	1.254	99	1	148	99	148	18	120	81	102	60	144	111
5	1.451	111	24	23	105	157	20	113	73	104	53	157	103
Av	1.282	100	10	122	99	148	13	121	79	100	66	146	107

Participant 5 Upright Up and Over

Figure Appendix 8 - 13 Participant 5 set position

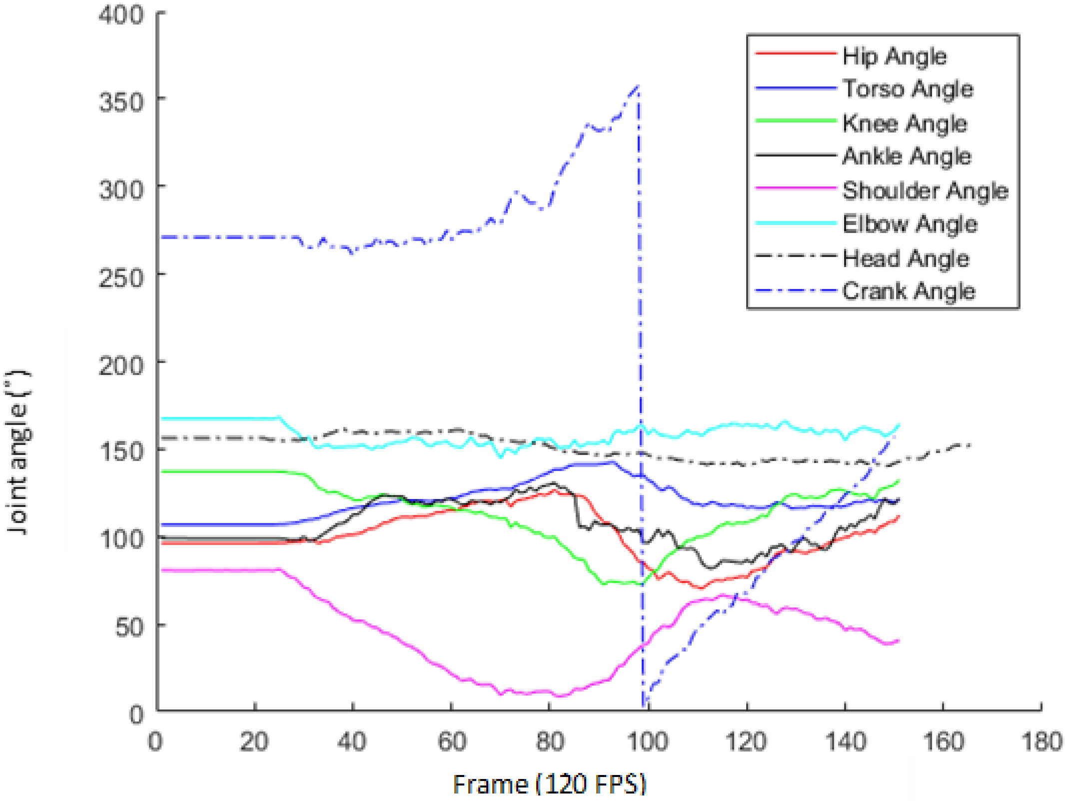

Figure Appendix 8 - 14 Participant 5 kinematic profile plot example

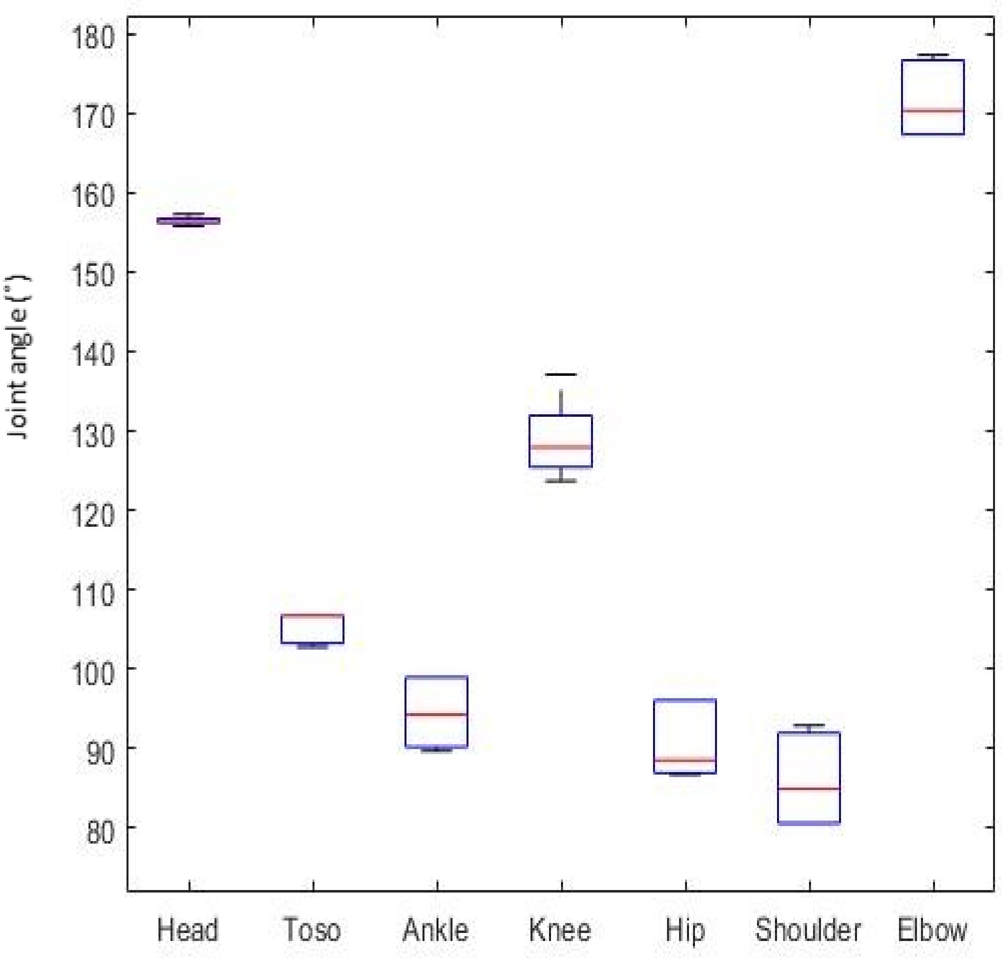

Figure Appendix 8 - 15 Participant 5 set position joint angles box plot

Table Appendix 8 – 5 Participant 5 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.379	90	13	145	98	84	16	119	87	28	92	80	109
2	1.385	89	1	151	94	73	26	115	78	26	89	78	111
3	1.386	93	1	150	91	81	25	113	82	25	70	81	111
4	1.393	95	26	151	96	79	26	119	71	25	57	72	107
5	1.394	93	25	151	97	149	23	115	85	4	85	86	111
Av	1.387	92	13	150	95	93	23	116	81	22	79	79	110

Participant 6 Upright Half Circle

Figure Appendix 8 - 16 Participant 6 set position

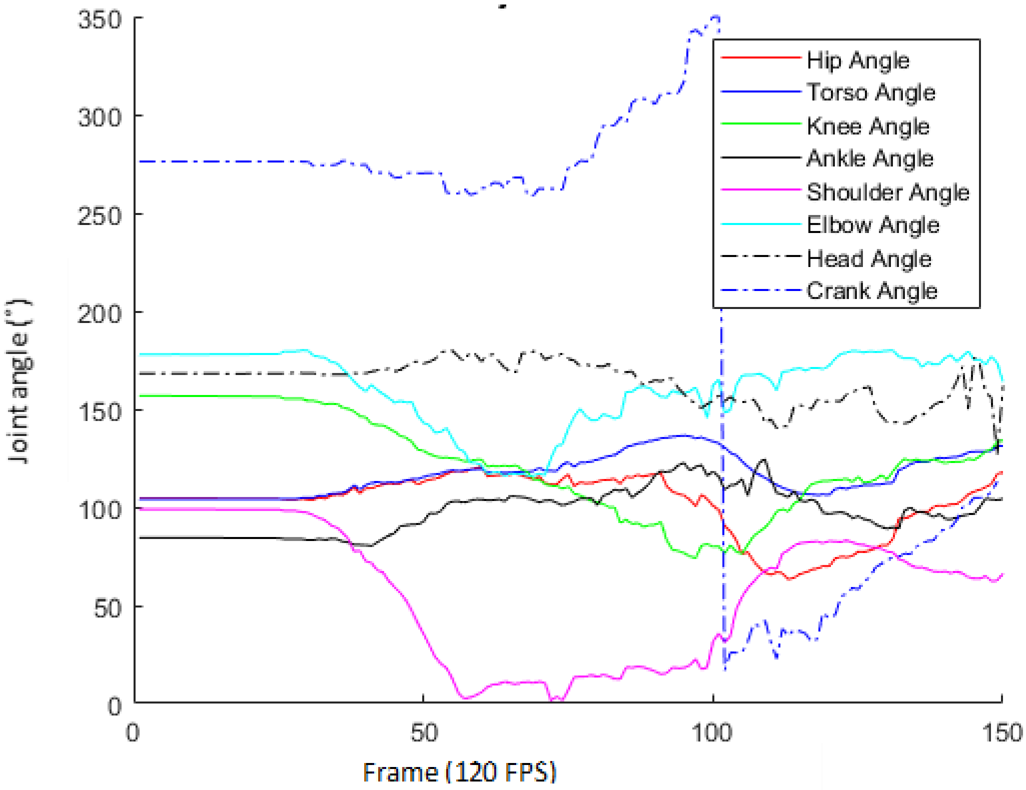

Figure Appendix 8 - 17 Participant 6 kinematic profile plot example

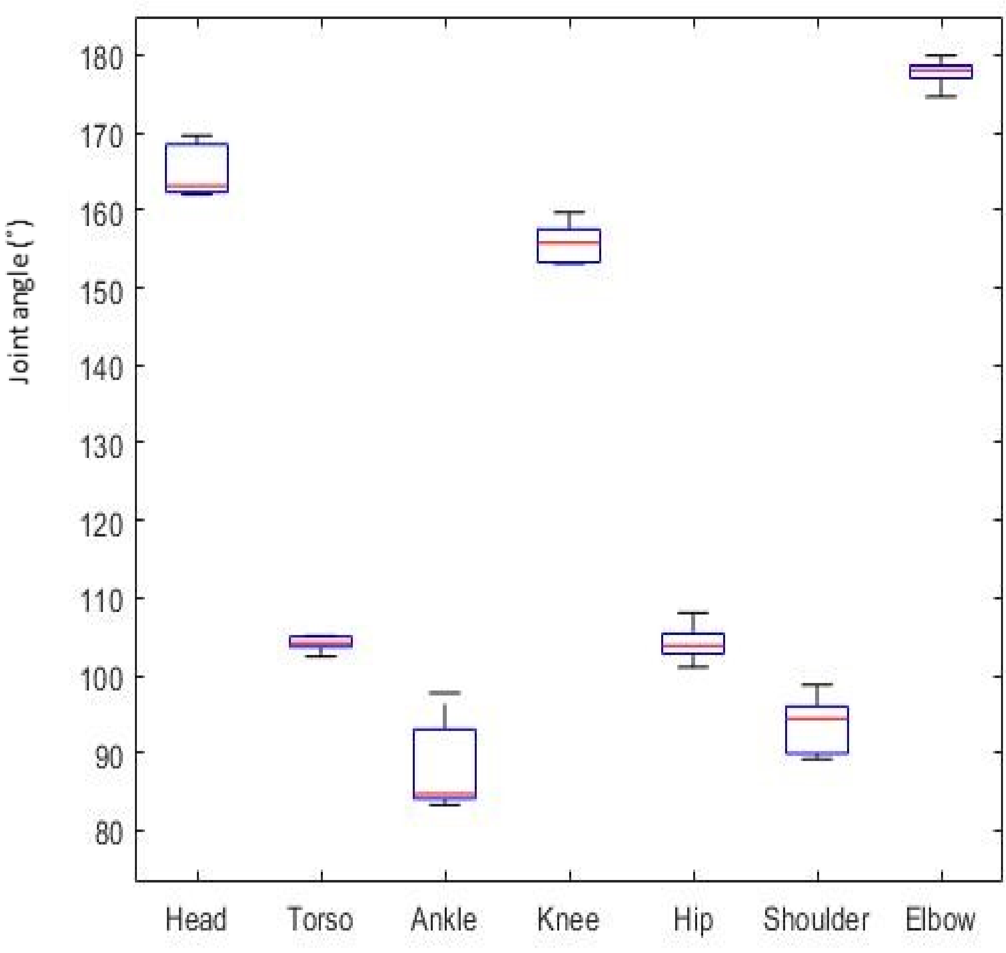

Figure Appendix 8 - 18 Participant 6 set position joint angles box plot

Table Appendix 8 - 6 Participant 6 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.362	93	20	4	102	151	21	36	67	27	58	88	112
2	1.362	96	3	23	101	148	17	38	58	10	62	78	110
3	1.4	95	19	4	96	100	21	37	71	3	62	87	110
4	1.409	95	3	1	97	109	3	41	72	29	64	60	113
5	1.47	105	36	5	110	118	27	48	75	32	63	88	121
Av	1.401	97	16	7	101	125	18	40	69	20	62	80	113

Participant 7 Upright Half Circle

Figure Appendix 8 - 19 Participant 7 set position

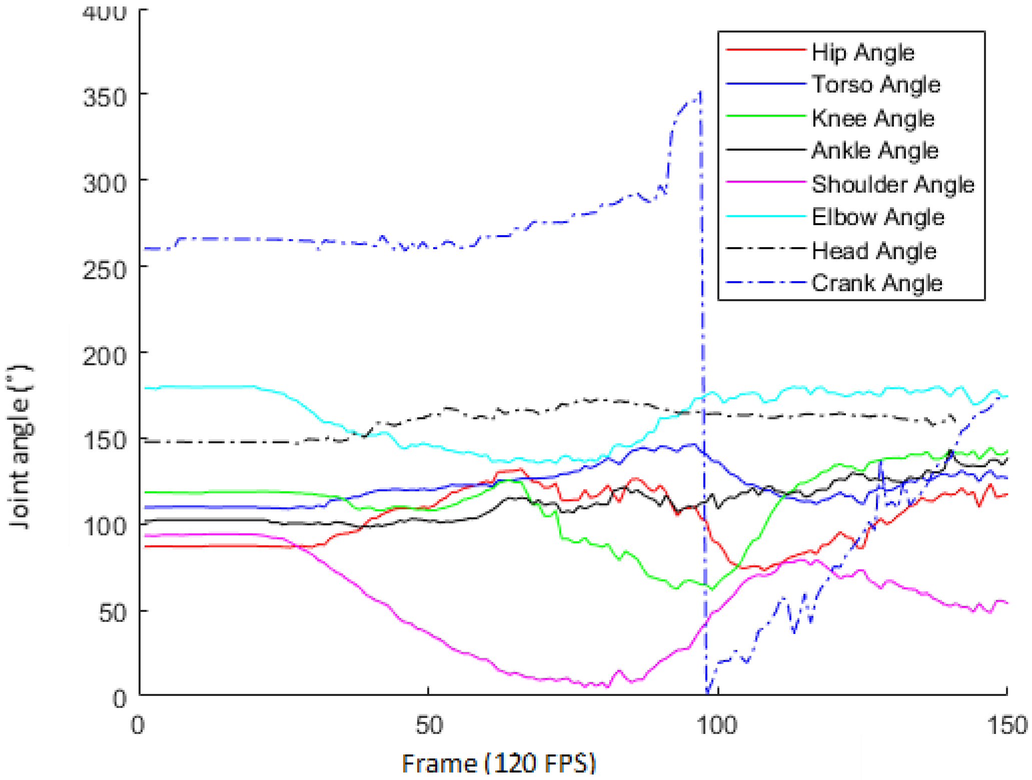

Figure Appendix 8 - 20 Participant 7 kinematic profile pot example

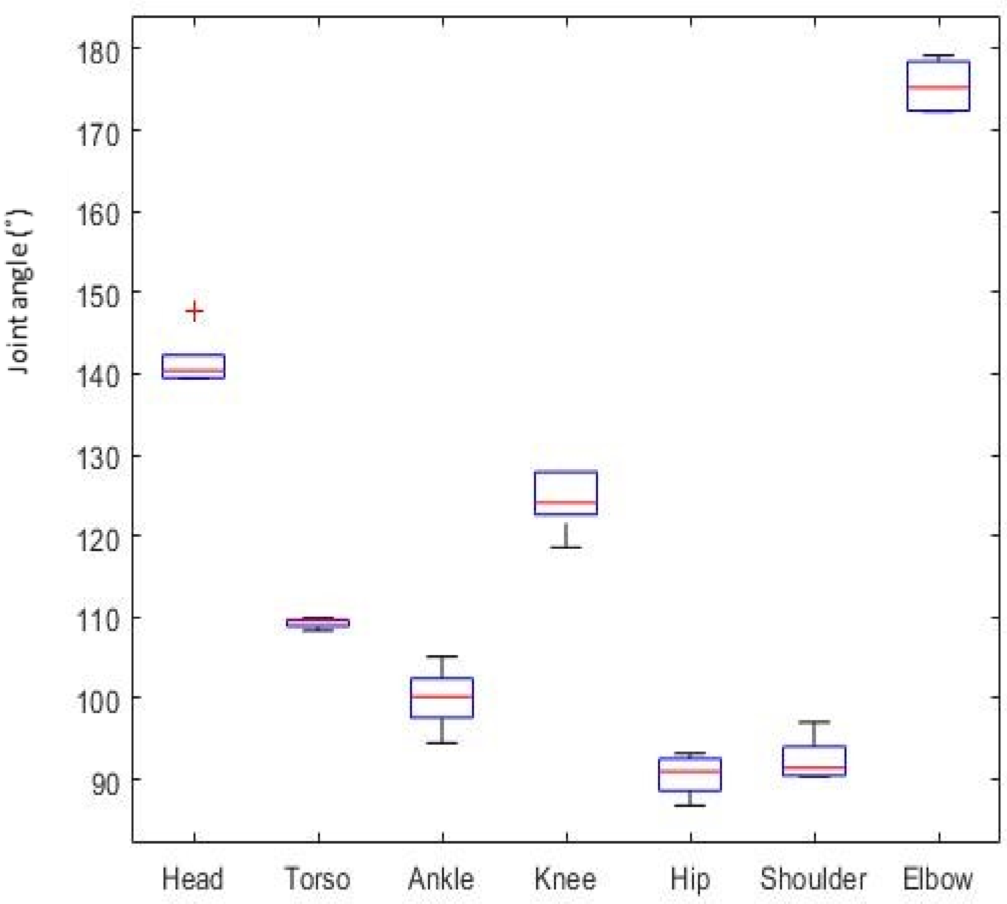

Figure Appendix 8 - 21 Participant 7 set position joint angle box plot

Table Appendix 8 – 7 Participant 7 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.347	96	26	147	99	140	12	38	81	142	72	66	108
2	1.372	94	23	131	99	149	11	48	92	103	53	81	114
3	1.373	94	23	143	100	147	5	41	91	149	58	90	112
4	1.379	93	19	117	93	100	8	31	70	115	70	80	108
5	1.383	94	29	139	95	146	1	28	70	116	68	69	109
Av	1.378	94	24	135	97	136	7	37	81	125	64	77	110

Participant 8 Back Hairpin

Figure Appendix 8 - 22 Participant 8 set position

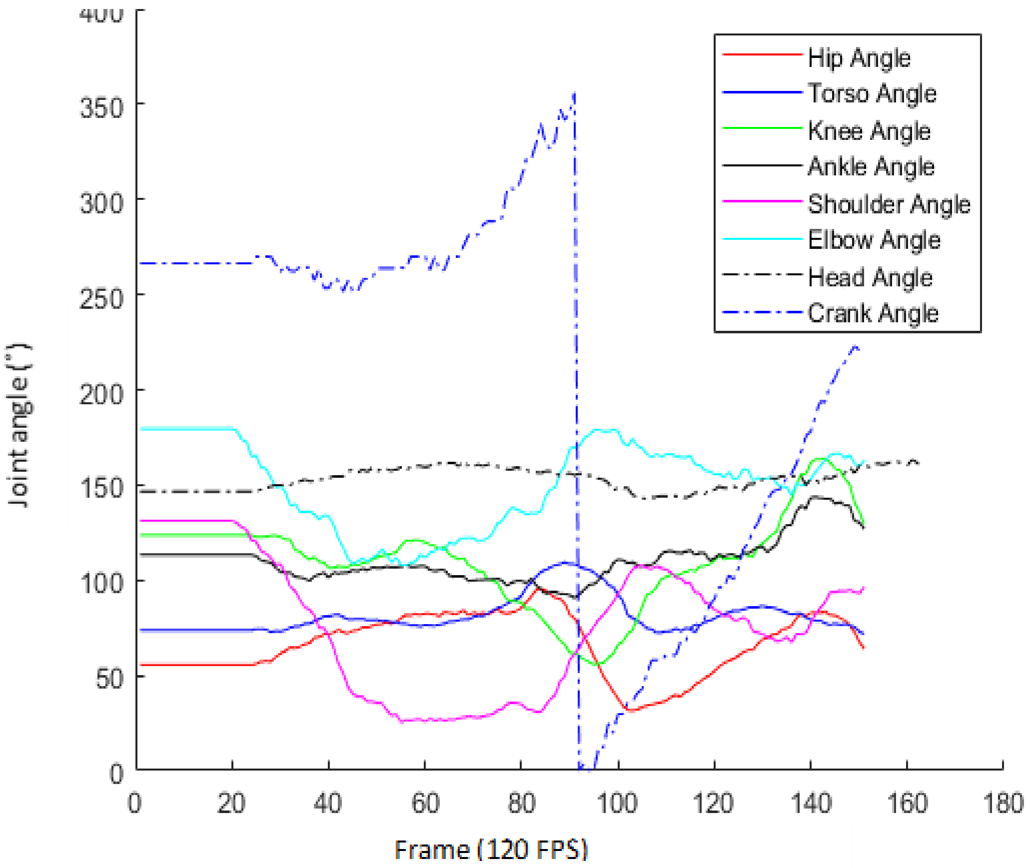

Figure Appendix 8 - 23 Participant 8 kinematic profile plot example

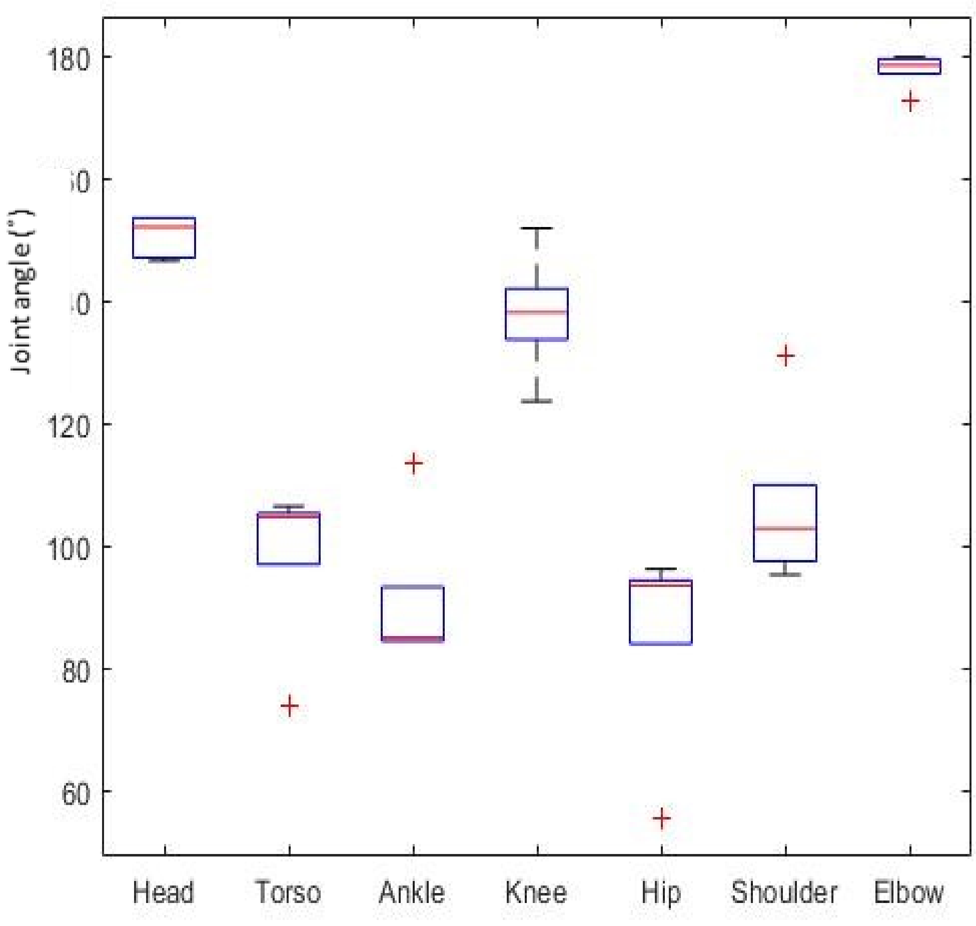

Figure Appendix 8 - 24 Participant 8 set position joint angle box plot

Table Appendix 8 - 8 Participant 8 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.188	89	18	141	95	140	18	42	82	100	47	142	108
2	1.197	99	1	148	99	148	18	41	81	116	60	144	111
3	1.199	93	25	144	96	144	24	33	79	116	53	141	108
4	1.203	94	24	145	98	144	1	49	64	101	58	142	105
5	1.204	93	20	142	96	142	22	34	89	100	50	142	107
Av	1.198	94	15	144	97	144	17	40	79	107	54	142	108

Participant 9 Angled, Up and Over

Figure Appendix 8 - 25 Participant 9 set position

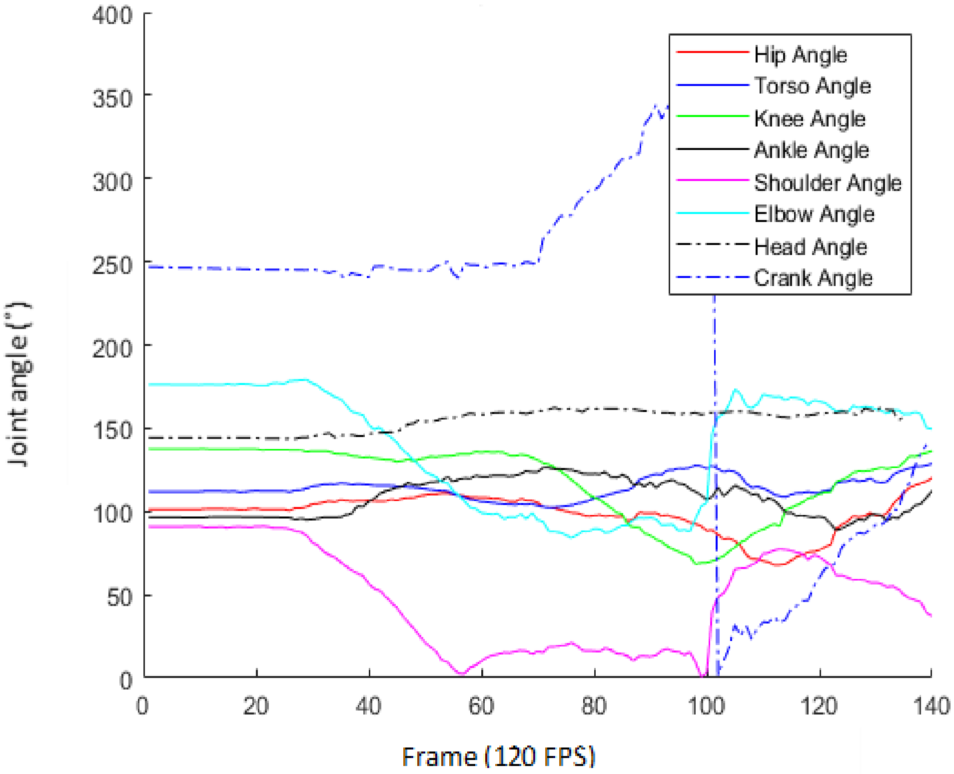

Figure Appendix 8 - 26 Participant 9 kinematic profile plot example

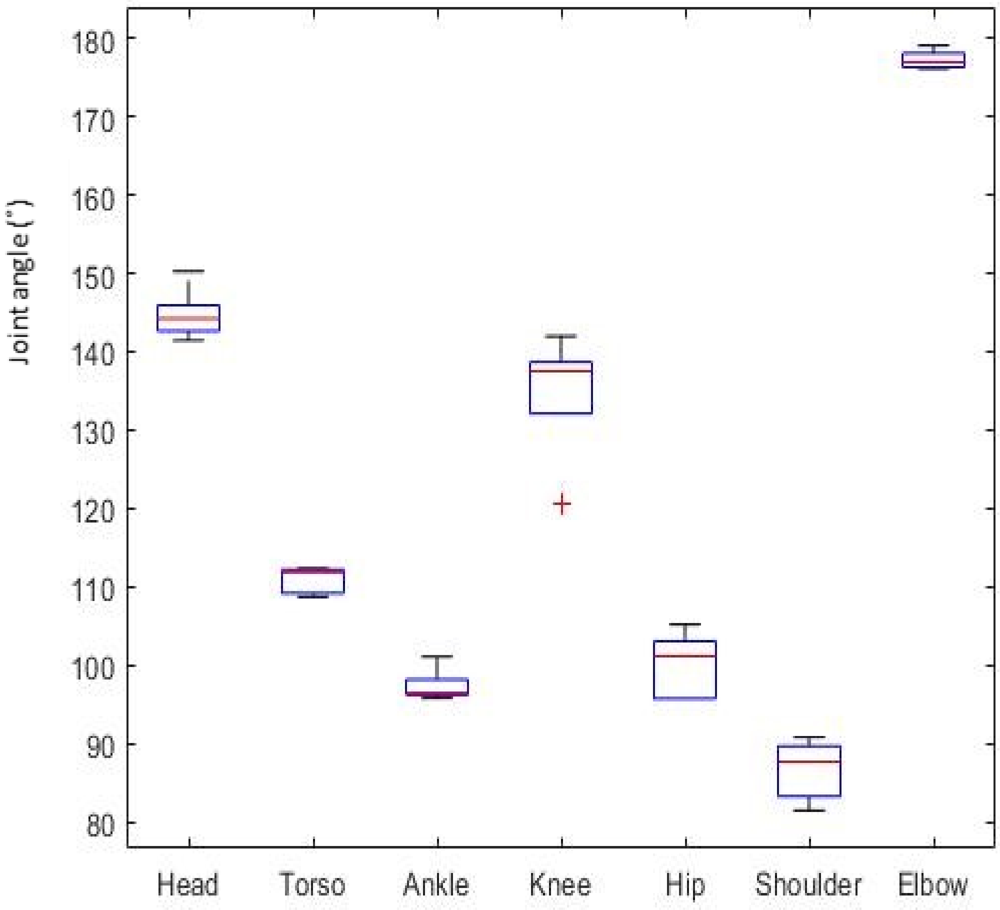

Figure Appendix 8 - 27 Participant 9 set position joint angle box plot

Table Appendix 8 - 9 Participant 9 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.253	98	72	150	98	71	10	123	99	29	76	140	112
2	1.27	99	77	150	103	78	19	129	58	19	63	149	116
3	1.322	96	24	145	100	52	24	99	61	21	62	150	105
4	1.331	100	79	139	99	83	25	117	78	21	56	139	113
5	1.437	78	58	151	96	64	1	120	84	21	52	151	107
Av	1.323	94	62	147	99	70	16	118	76	22	62	146	111

Participant 10 Angled Hairpin

Figure Appendix 8 - 28 Participant 10 set position

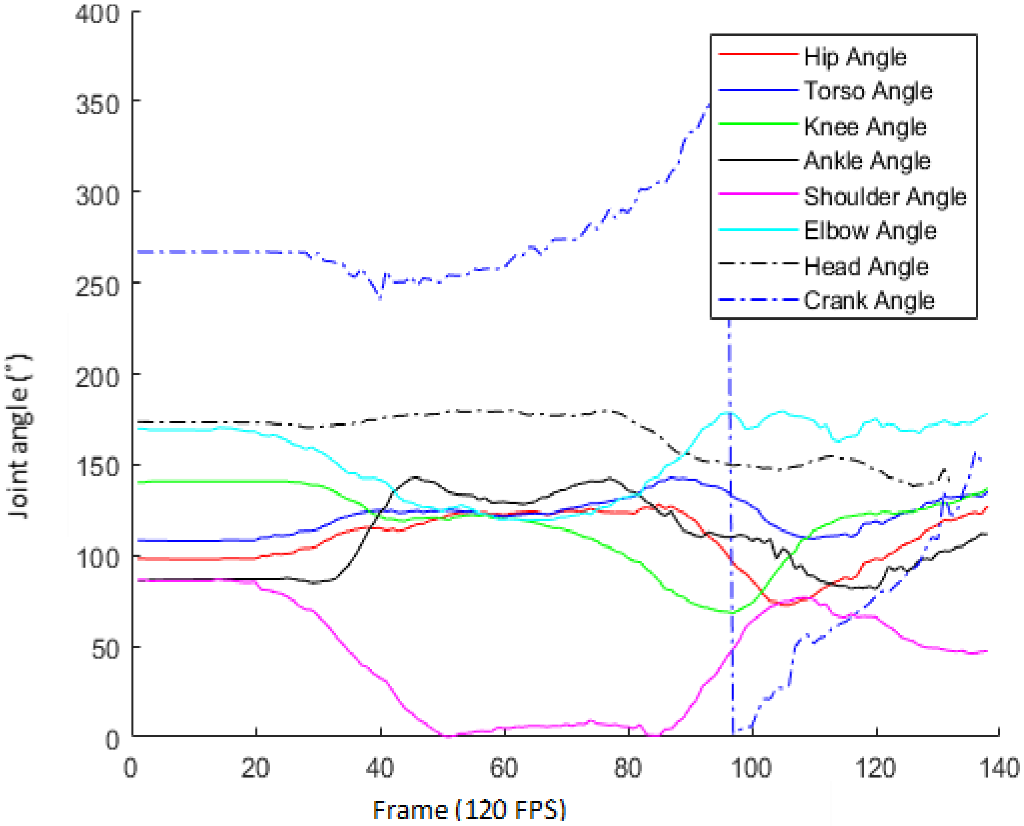

Figure Appendix 8 - 29 Participant 10 kinematic profile plot example

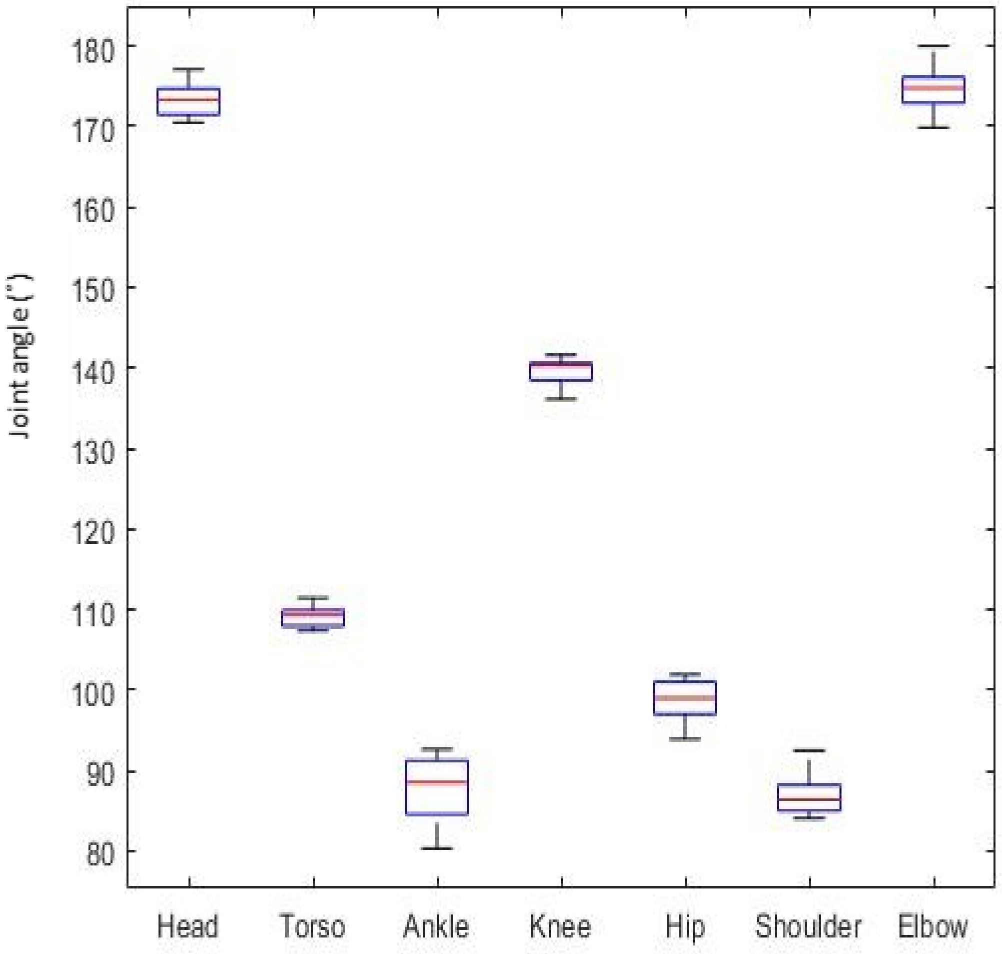

Figure Appendix 8 - 30 Participant 10 set position joint angle box plot

Table Appendix 8 - 10 Participant 10 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.215	87	14	138	97	46	14	120	51	105	64	85	105
2	1.241	91	1	148	97	79	1	119	82	100	60	79	106
3	1.251	86	3	151	97	47	3	119	85	143	70	81	104
4	1.253-1	84	5	147	97	75	11	118	62	101	72	67	103
5	1.253-2	89	5	138	93	74	5	115	83	138	68	74	102
Av	1.242	87	6	144	96	64	7	118	73	117	67	77	104

Participant 11 Angled Half Circle

Figure Appendix 8 - 31 Participant 11 set position

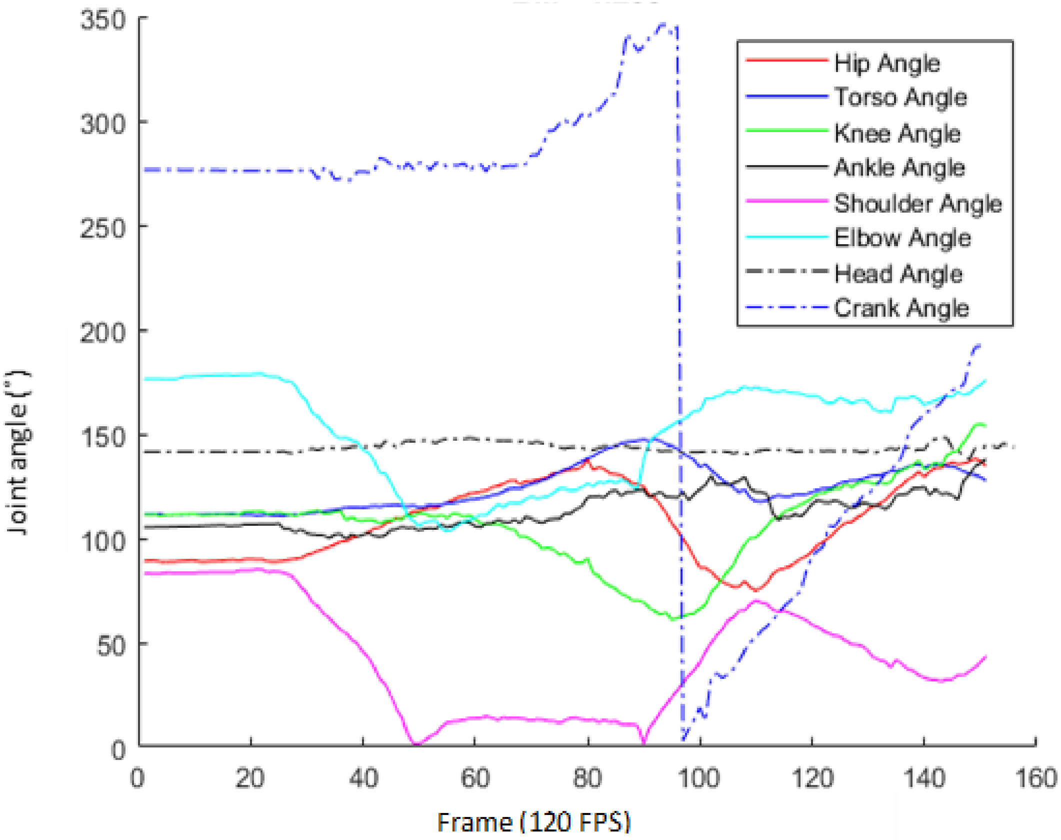

Figure Appendix 8 - 32 Participant 11 kinematic profile plot example

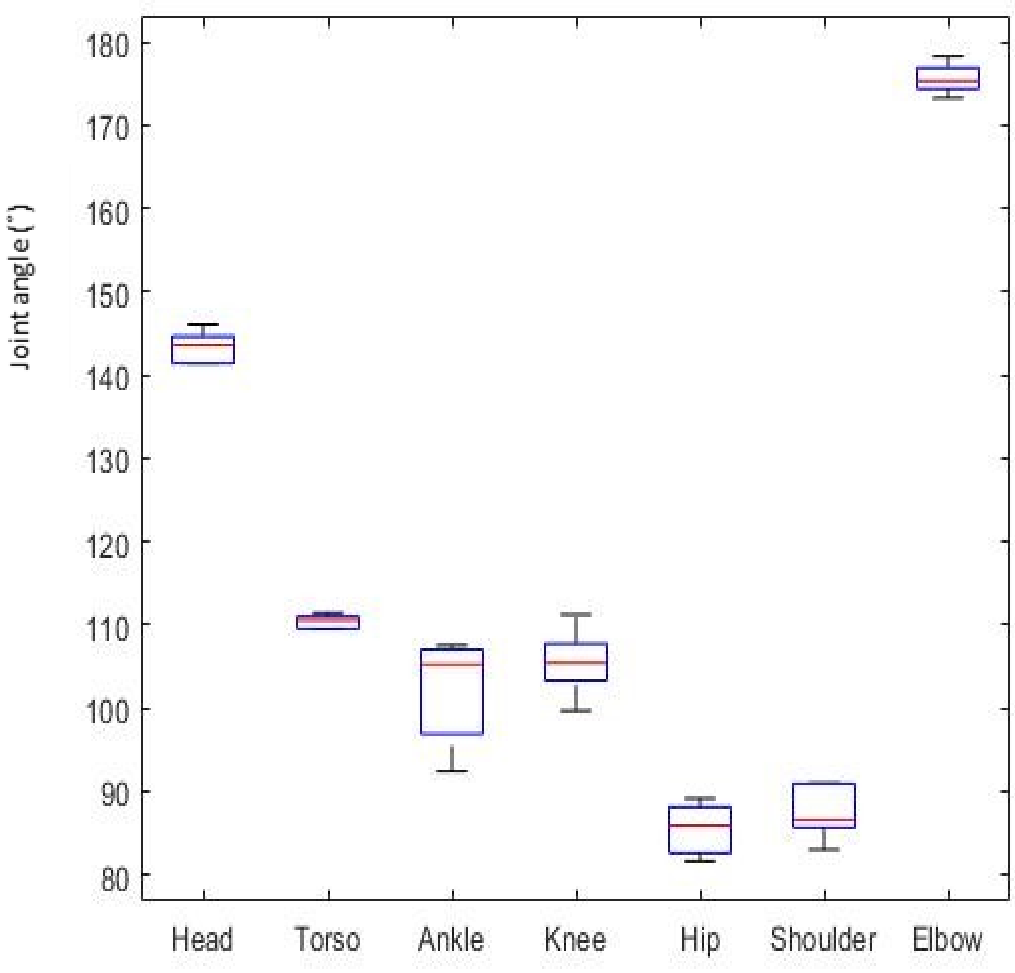

Figure Appendix 8 - 33 Participant 11 set position joint angle box plot

Table Appendix 8 - 11 Participant 11 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.255	92	26	150	95	150	21	37	90	22	55	149	110
2	1.273	93	1	151	97	109	1	39	52	28	54	150	111
3	1.273	81	17	133	85	133	11	27	41	9	48	132	103
4	1.281	92	22	151	97	151	22	38	52	31	55	148	111
5	1.285	97	30	151	100	120	22	92	74	117	60	147	112
Av	1.273	91	19	147	95	133	15	47	62	41	54	145	109

Participant 12 Upright Up and Over

Figure Appendix 8 - 34 Participant 12 set position

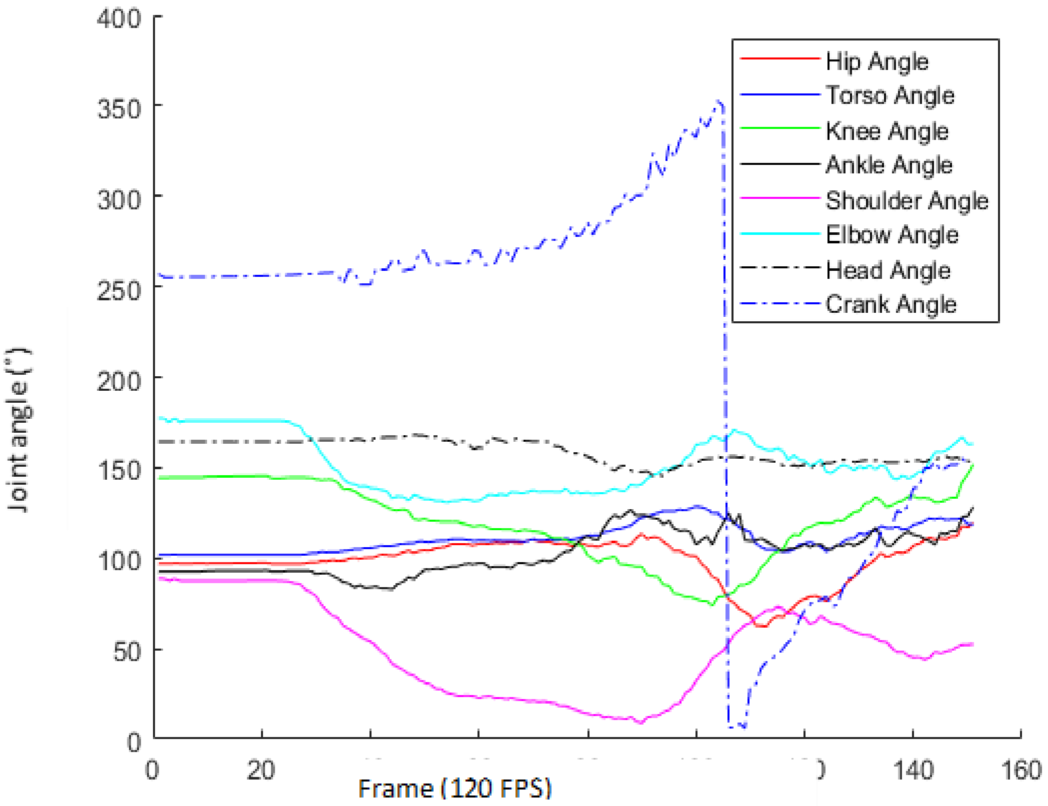

Figure Appendix 8 - 35 Participant 12 kinematic profile plot example

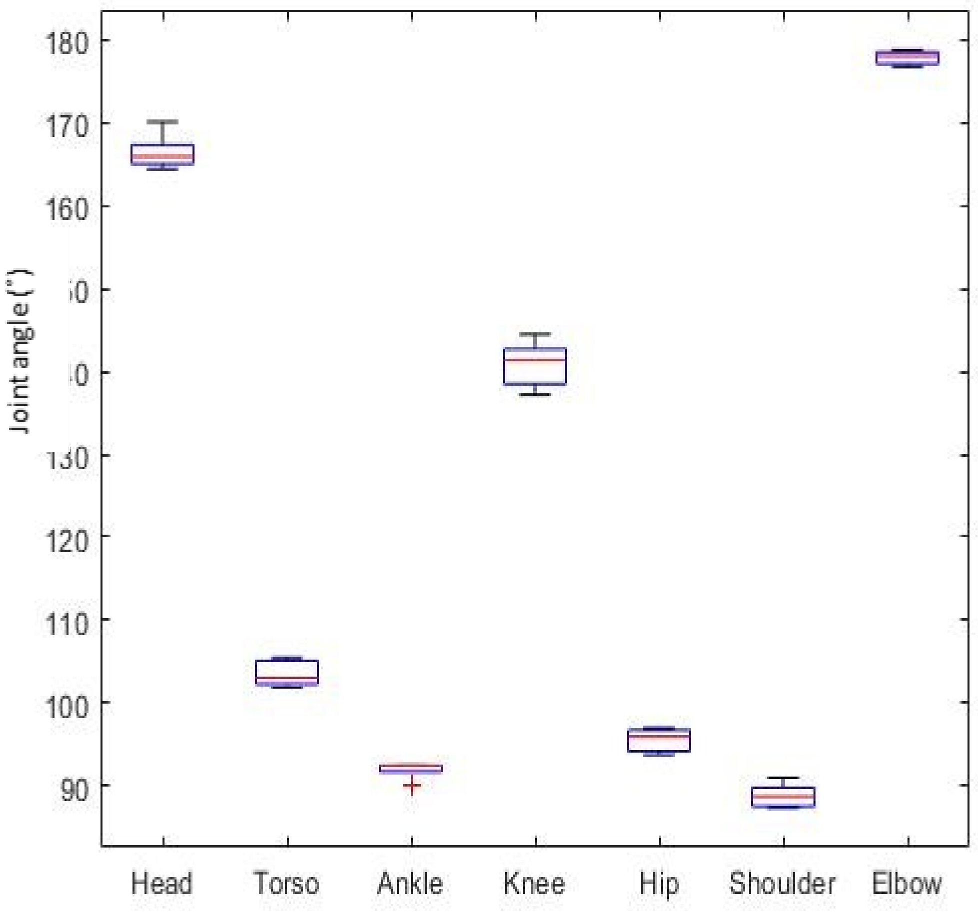

Figure Appendix 8 - 36 Participant 12 set position joint angle box plot

Table Appendix 8 - 12 Participant 12 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.248	87	115	112	90	79	10	25	78	15	63	118	104
2	1.251	144	117	150	99	150	17	35	84	17	81	145	112
3	1.263	100	124	151	103	151	1	44	90	1	54	150	113
4	1.269	94	123	151	102	149	21	33	88	21	65	146	120
5	1.276	143	117	138	101	87	3	34	89	1	69	143	114
Av	1.261	113	119	140	99	123	10	34	85	11	66	140	113

Participant 13 Upright Half Circle

Figure Appendix 8 – 37 Participant 13 set position

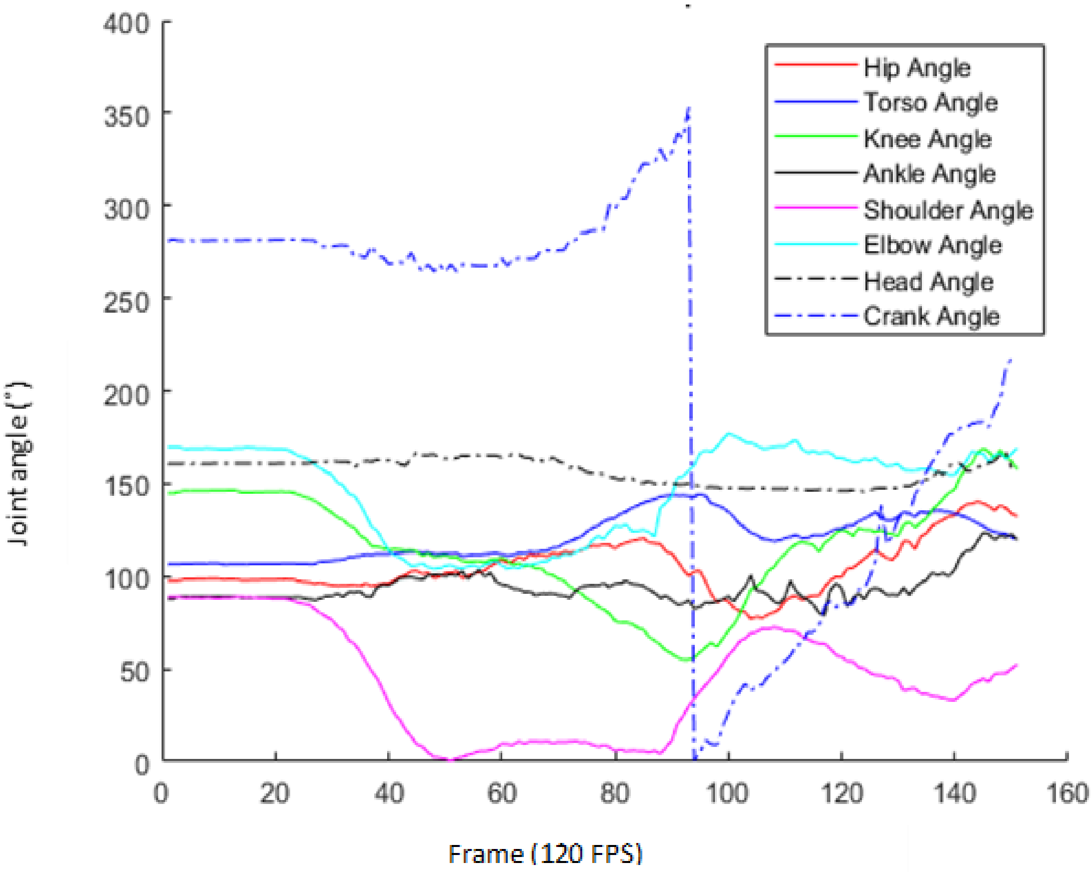

Figure Appendix 8 - 38 Participant 13 kinematic profile plot example

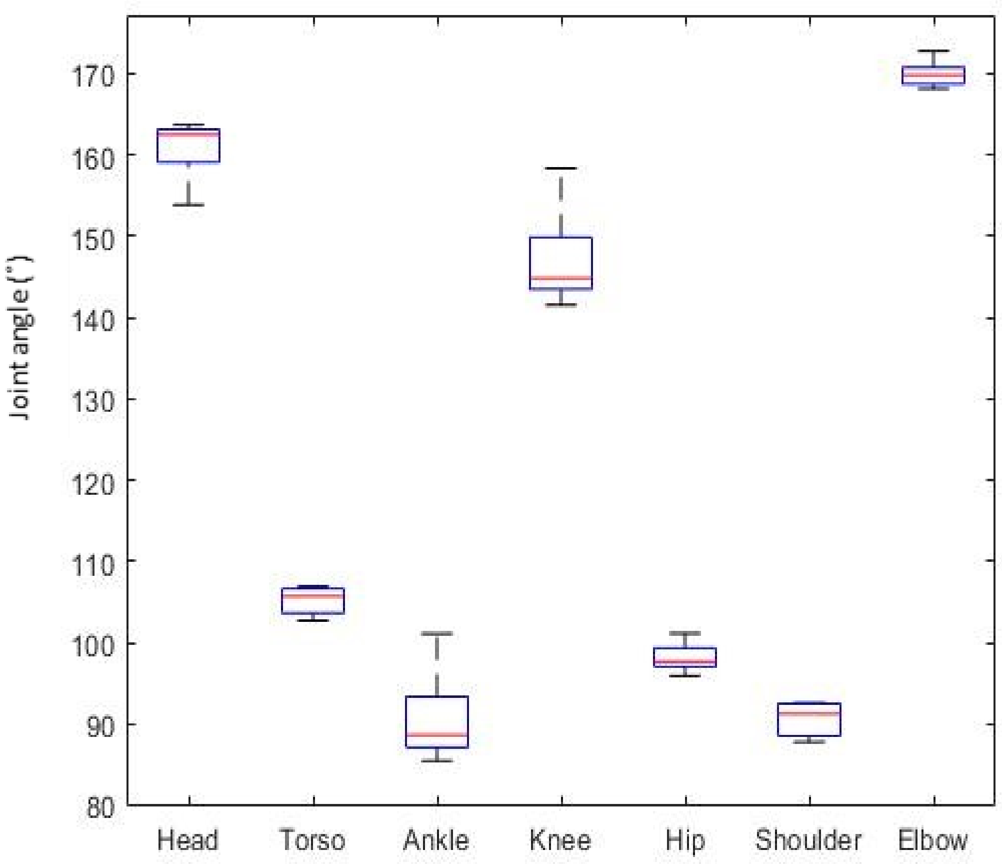

Figure Appendix 8 - 39 Participant 13 set position joint angle boxplot

Table Appendix 8 - 13 Participant 13 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.242-1	95	11	145	92	145	3	27	51	100	61	144	104
2	1.242-2	91	13	145	96	145	18	23	87	110	52	144	106
3	1.254	92	1	150	97	146	1	30	58	115	48	145	106
4	1.258	93	3	149	94	148	9	37	52	103	58	147	111
5	1.266	95	27	151	94	150	12	33	78	101	50	149	110
Av	1.252	93	11	148	95	147	7	30	65	106	54	146	107

Participant 14 Angled Up and Over

Figure Appendix 8 - 40 Participant 14 set position

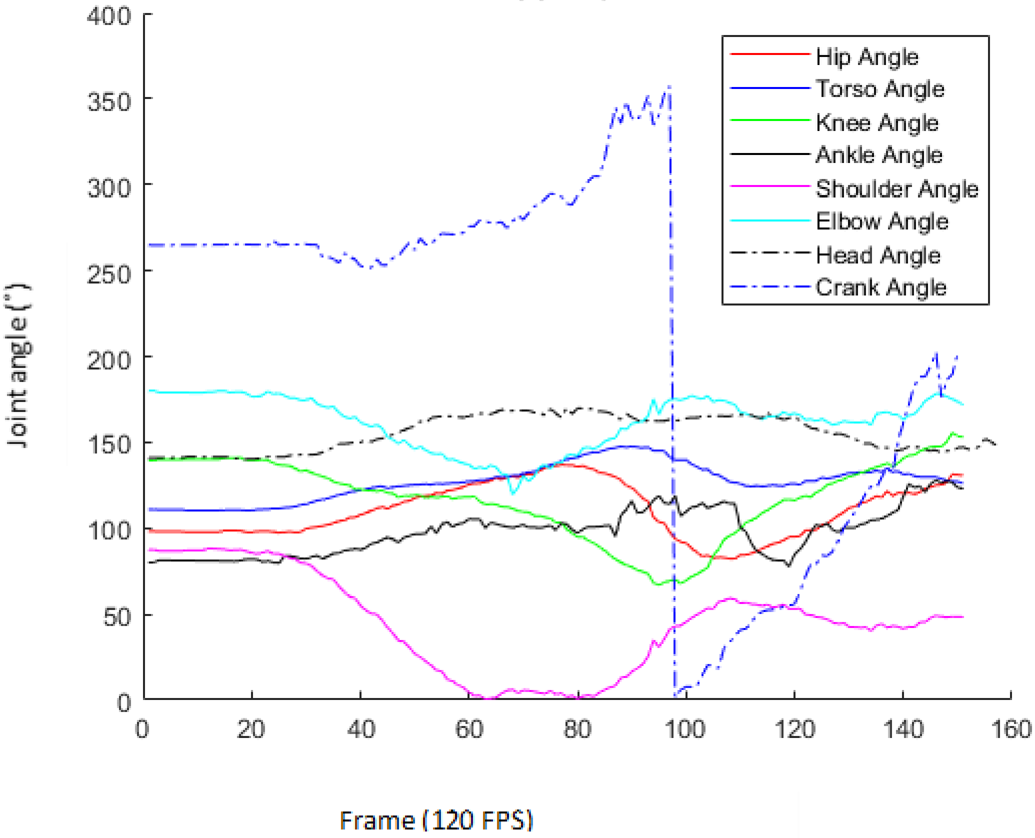

Figure Appendix 8 - 41 Participant 14 kinematic profile plot example

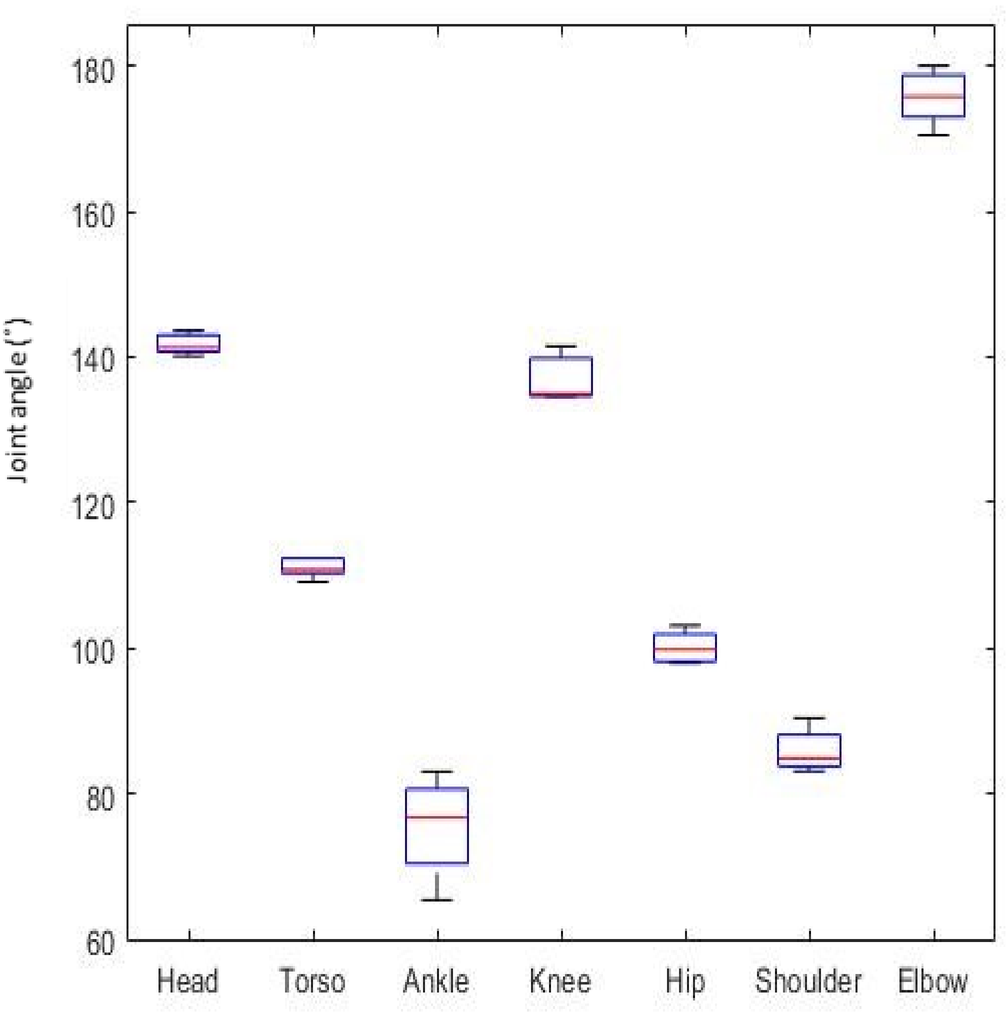

Figure Appendix 8 - 42 Participant 14 set position joint angle boxplot

Table Appendix 8 - 14 Participant 14 timing of events - Shaded cell values have been altered for final results

#	Kink time	Max torso	Min torso	Max knee	Min knee	Max ankle	Max shoulder	Min ankle	Min shoulder	Max elbow	Min elbow	Max hip	Min hip
1	1.324	92	8	151	97	151	22	30	66	103	76	150	107
2	1.327	90	8	149	95	146	12	25	63	102	68	150	108
3	1.33	92	13	151	98	145	13	15	72	103	66	150	106
4	1.332	90	11	145	95	144	12	22	59	103	71	145	109
5	1.334	91	17	151	96	151	16	29	79	106	69	150	112
Av	1.329	91	11	149	96	147	15	24	68	103	70	149	108