Breaststroke Biomechanics in Elite Swimmers: Temporal Characteristics, Hand, Knee and Foot Path Patterns, and Physical Attributes

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Breaststroke Biomechanics in Elite Swimmers: Temporal Characteristics, Hand, Knee and Foot Path Patterns, and Physical Attributes

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Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Signed ______________________________

Date 17/10/2023.

Acknowledgements

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Can you believe we reached another academic milestone? Thank you for your continuous support from the pool to applied sports science and again to academia. There is no way I would have discovered a passion for sports science or found my way into the high-performance network without your help and for this I am extremely grateful. Thank you again for leading from the front, teaching me to take the opportunities presented or if they are not available to make my own. Very excited to see you thriving in a world outside of sport and wish you every success moving forward.

Dr. Simon Pearson

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The Queensland Academy of Sport and the Gold Coast Hub

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Abstract

Biomechanical analysis is frequently applied in elite swimming with intent to optimise competition performance. When applied to breaststroke swimming, biomechanical analysis has previously revealed kinematic and neuromuscular activation patterns associated with performance excellence. To provide coaches, athletes and applied sports practitioners with additional insight into the biomechanical factors associated with elite breaststroke swimming performance, this thesis investigated three topic areas of applied biomechanics that have not been investigated heavily within the existing scientific literature. Specifically, this thesis aimed to evaluate the relationships of temporal characteristics, path patterns of the hand, knee and foot, and physical attributes with breaststroke performance in an elite breaststroke population.

To evaluate relationships between selected kinematic parameters and breaststroke swimming performance, three original studies (Chapters Three, Four and Five) were designed and implemented. The first original study (Chapter Three) characterised the temporal properties of elite breaststroke swimmers during competition in the 100 m and 200 m events. Improving on the ecological validity of previous temporal study through the investigation of temporal patterns in competition when compared to 25 m paced efforts, this study examined the temporal patterns utilised in 86 elite breaststroke swimming races. Findings supported the existence of temporal pattern differences between strokes typically used during 100 m and 200 m events, and between male and female athletes. Collectively, distance- and sex-based temporal pattern differences emphasised a need for coaches to individualise breaststroke temporal patterns based on event demands and sex-related morphological characteristics of the athlete.

Adding further context to findings of Chapter Three, the original study contained in Chapter Four described associations between path patterns of the hand, knee and foot segments and swimming velocity in elite breaststroke swimmers at 100 m pace. Study of these associations involved estimation of the three-dimensional (3D) paths of the hand, knee and foot from eleven elite breaststroke swimmers. Three-dimensional paths were subsequently used to calculate the total distance travelled, maximum lateral position and relative lateral position of key body segments across

temporal phases of the stroke cycle. Associations between body segment displacement characteristics and hip velocity across the stroke cycle were then assessed using correlation analysis. As the first known study to investigate 3D segment paths in an elite breaststroke population, findings of Chapter Four could result in a shift in the prescription of optimal breaststroke technique. Results indicated that swimmers should aim to follow a direct hand path from glide position to maximal lateral position during the outsweep phase, follow a large hand path during the insweep phase and achieve relative lateral proximity of the hip, knee and foot at the start of kick propulsion to maintain higher average velocity across the stroke cycle.

To understand how an individual's physical capacities could mediate propulsive velocity (average and/or peak velocity reached throughout the propulsive pull and propulsive kick phases of the stroke cycle), the study contained in Chapter Five determined the relationships between dryland strength-power measures and propulsive velocity in elite breaststroke swimmers. Dryland strength-power measures of mean chin up velocity and countermovement jump height were assessed in eleven elite breaststroke athletes and subsequently correlated to the average velocity maintained during breaststroke propulsive pull and propulsive kick phases at maximal, 100 m and 200 m paces. Strong associations between dryland strength-power measures and propulsive velocity were most frequently reported at 100 m and maximal paces when compared to 200 m pace. These associations were consistently positive, indicating athletes who performed better on dryland strength-power measures achieved higher average velocity during both propulsive pull and propulsive kick phases. Findings of Chapter Five supported a mediating effect of individual strength-power characteristics on propulsive velocity in elite breaststroke swimmers. This finding should be considered by strength and conditioning coaches in the prescription of dryland training programs, specifically those designed for sprint breaststroke swimmers.

Included to further detail the methodological processes outlined in Chapter Four, Chapter Six synthesised the existing research and theory associated with 3D video-based analysis in aquatic environments. Synthesis of this information justified the methodology reported in Chapter Four and helped to position this thesis within the existing research. Information contained within this chapter can also be used as a resource for future practitioners with an interest in conducting 3D video-based analysis during future research investigations.

The series of original studies and supplementary methodology chapter presented in this thesis provided insight that coaches, swimmers and applied sports practitioners can use to inform training design for elite breaststroke swimmers. Throughout this thesis the interplay of temporal characteristics, path patterns of the hand, knee and foot and physical attributes on swimming velocity was demonstrated. Results evidenced the need to tailor training design within an elite breaststroke swimming population to optimise competition performance.

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BB	Biceps brachii
BF	Bicep femoris
CP1	Coordination phase one
CP2	Coordination phase two
CRP	Continuous relative phase
CSV	Comma separated values
DLC	Deep Lab Cut
DLT	Direct linear transformation
EMG	Electromyography
eWPS	Effective work per stroke
FINA	Fédération Internationale De Natation
GAS	Gastrocnemius
IBFP	Index of flat breaststroke propulsion
ICC	Interclass correlation coefficient
iEMG	Total integrated EMG
ISAK	International Society for the Advancement of Kinanthropometry
IVV	Intracyclic velocity variation
LED	Light emitting diode
PM	Pectoralis major
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RF	Rectus femoris
ROM	Range of motion
SI	Stroke index
SL	Stroke length
SR	Stroke rate
$T1_a$	Temporal gap one ^{a}
$T1_b$	Temporal gap one ^{b}
T2	Temporal gap two
T3	Temporal gap three
T4	Temporal gap four

TA	Tibialis anterior
TB	Triceps brachii
TRA	Trapezius
TT	Time-trial

List of Peer-Reviewed Publications During Doctoral Candidature

Publications arising from this thesis.

Nicol, E., Adani, N., Lin, B., & Tor, E. (2021). The temporal analysis of elite breaststroke swimming during competition. *Sports Biomechanics*, 1-13. https://doi.org/10.1080/14763141.2021.1975810

Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). Stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics in elite breaststroke swimming: a systematic review. *Sports Medicine-Open*, *8*(1), 1-24.

Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). The association of range of motion, dryland strength–power, anthropometry, and velocity in elite breaststroke swimmers. *International Journal of Sports Physiology and Performance*, *17*(8), 1222-1230.

Submitted to *Journal of Sports Sciences; "*Hand, Knee and Foot Path Patterns in Elite Breaststroke Swimmers and their Association to Velocity at 100 m Pace", Nicol E, Pearson S, Papic, C., Saxby D, Minahan C, & Tor E.

Additional publications not included in this thesis that have been made during this candidature.

Tor, E., Nicol, E., & Sweeting, A. (2022). Collecting and Presenting Data for Performance Impact in Elite Sport: Finding the Right Balance between Humans and Machines. In *Interactive Sports Technologies* (pp. 60-78). Routledge.

List of Presentations During Doctoral Candidature

Nicol, E. Timing Patterns in Elite Breaststroke Swimming. National Flippers Program - Coaches Workshop. January 2023, Gold Coast, Australia.

Nicol, E. All in Good Time: The Temporal Characteristics of Elite Breaststroke Swimmers. Queensland Academy of Sport IGNITE 2032 Conference. November 2022, Brisbane, Australia.

Nicol, E. PhD in Sport: Learnings from and Within the Hub. Swimming Australia Performance Support Workshop. October 2022, Brisbane, Australia.

Thomas, R, & Nicol, E. Race Skills: Starts and Turns, SwimCon2022. September 2022, Gold Coast, Australia.

Nicol, E, & Pearson, S. Breaststroke Biomechanics in Elite Swimmers: Temporal Characteristics, Velocity Patterns and Physical Attributes. Movement Science Forum. October 2021, online.

Nicol, E, Pearson S, & Tor, E. Breaststroke Biomechanics in Elite Swimmers: Temporal Characteristics, Velocity Patterns and Physical Attributes. International Analyst Conference. February 2021, online.

Nicol, E. Temporal Analysis of 100 m World Record Breaststroke Swimming. ESSA Twitter Conference. November 2020, online.

List of Applied Sports Science Servicing Milestones During Doctoral Candidature

Performance Scientist, Queensland Academy of Sport
September 2019 – present

Movement Scientist – Next Generation Freestyle Relay Camp, Swimming Australia
February 2023

Movement Scientist – National Flippers Camp, Swimming Australia
January 2023

Movement Scientist – Next Generation Freestyle Relay Camp, Swimming Australia
September 2022

Movement Scientist – National Event Camp, Swimming Australia
February 2021

Movement Scientist – National Flippers Camp, Swimming Australia
January 2020

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Acknowledgement of Papers Included in This Thesis

Section 9.1 of the Griffith University Code for the Responsible Conduct of Research ("Criteria for Authorship"), in accordance with Section 5 of the Australian Code for the Responsible Conduct of Research, states:

To be named as an author, a researcher must have made a substantial scholarly contribution to the creative or scholarly work that constitutes the research output, and be able to take public responsibility for at least that part of the work they contributed. Attribution of authorship depends to some extent on the discipline and publisher policies, but in all cases, authorship must be based on substantial contributions in a combination of one or more of:

- conception and design of the research project
- analysis and interpretation of research data
- drafting or making significant parts of the creative or scholarly work or critically revising it so as to contribute significantly to the final output.

Section 9.3 of the Griffith University Code ("Responsibilities of Researchers"), in accordance with Section 5 of the Australian Code, states:

Researchers are expected to:

- Offer authorship to all people, including research trainees, who meet the criteria for authorship listed above, but only those people.
- Accept or decline offers of authorship promptly in writing.
- Include in the list of authors only those who have accepted authorship.
- Appoint one author to be the executive author to record authorship and manage correspondence about the work with the publisher and other interested parties.
- Acknowledge all those who have contributed to the research, facilities or materials but who do not qualify as authors, such as research assistants, technical staff, and advisors on cultural or community knowledge.
- Obtain written consent to name individuals.

Included in this thesis are papers in Chapters Two, Three, Four and Five which are co-authored with other researchers. My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details for these papers including all authors, are:

Chapter Two: Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). Stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics in elite breaststroke swimming: a systematic review. *Sports Medicine-Open*, *8*(1), 1-24.

Chapter Three: Nicol, E., Adani, N., Lin, B., & Tor, E. (2021). The temporal analysis of elite breaststroke swimming during competition. *Sports Biomechanics*, 1-13. https://doi.org/10.1080/14763141.2021.1975810

Chapter Four: Submitted to *Journal of Sports Sciences; "*Hand, Knee and Foot Path Patterns in Elite Breaststroke Swimmers and their Association to Velocity at 100 m Pace", Nicol E, Pearson S, Papic, C., Saxby D, Minahan C, & Tor E.

Chapter Five: Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). The association of range of motion, dryland strength–power, anthropometry, and velocity in elite breaststroke swimmers. *International Journal of Sports Physiology and Performance*, *17*(8), 1222-1230.

Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

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Chapter One: Introduction & Thesis Outline

1.1 Introduction

Biomechanical analysis plays a pivotal role in optimising elite swimming performance. Namely, biomechanical analysis enables the quantification of technical performance, tracking of performance changes and the identification of targets for improvement, through the application of biomechanical principles (Barbosa et al., 2021; Mason, 2005). When applied to elite swimming biomechanical analysis is typically categorised into two areas, stroke mechanics and skill performance (Barbosa et al., 2021). In this sporting context, 'skill performance' refers to the technical quality of starts, turns and finishes, whereas 'stroke mechanics' refers to the mechanics of cyclic surface swimming.

Central to investigation in this thesis are the stroke mechanics of breaststroke swimming. Although all four swimming strokes have been the subject of biomechanical study, several mechanical features are unique to breaststroke swimming. Specifically, breaststroke swimming is characterised by two discontinuous propulsive phases (Leblanc et al., 2006; Takagi et al., 2004), long body glide times and underwater limb recoveries (Seifert et al., 2011). Breaststroke swimming is consequently associated with high intra-cyclic velocity variation and the slowest mean velocity when compared to the remaining competitive strokes.

Previous biomechanical analysis of elite breaststroke swimming has greatly contributed to our current understanding of breaststroke performance. This research has established several kinematic and neuromuscular activation pattern differences between groups based on race distance, athlete sex and performance level. The list of biomechanical parameters that have been studied for their relation to elite breaststroke swimming however, is not exhaustive and there are certain biomechanical parameters that likely mediate elite breaststroke performance that are yet to be investigated. The interaction between biomechanical parameters and their effect on elite breaststroke swimming performance is also yet to be robustly examined. These above-mentioned gaps within the existing literature limit the knowledge base that can be used to inform training design for the optimisation of competition performance in elite breaststroke swimming.

Three topic areas of applied biomechanics that have not been investigated heavily within the existing literature comprise the present program of research: 1. temporal characteristics in competition, 2. individual hand, knee and foot path patterns and 3. physical attributes of elite breaststroke swimmers. These areas were selected for study due to their frequent reference in applied training and competition settings and in the case of physical attributes, the frequent prescription of dryland training in elite swimming training programs.

Knowledge generated from investigation across these topic areas will enrich existing understanding of how biomechanics affect elite breaststroke swimming performance. More specifically, it will provide further insight into the ways in which temporal patterns, hand, knee and foot path patterns, and physical attributes vary between elite breaststroke swimmers and can be manipulated to increase swimming velocity. Additional insights provided through this thesis will better place coaches, athletes and applied sports practitioners to develop training interventions for the improvement of elite breaststroke swimming performance.

1.2 Research Aims

1.2.1 General Aims

This thesis aims to evaluate the relationship of temporal characteristics, path patterns of the hand, knee and foot, and physical attributes with breaststroke performance within populations of elite breaststroke swimmers.

1.2.2 Specific Aims

1. Characterise the temporal properties of elite breaststroke swimmers during competition and determine the temporal parameters with greatest importance to overall race time during 100 m and 200 m events.
2. Describe the associations between the path patterns of the hand, knee and foot, and swimming velocity in elite breaststroke swimmers at 100 m pace.
3. Develop a physical profile of elite breaststroke swimmers and evaluate the relationship between dryland strength-power measures and stroke kinematics.

1.3 Thesis Structure

This thesis is presented as a series of peer-reviewed journal articles and supplementary chapters that contextualise the research problem, discuss the interrelatedness of subject areas and further detail key methodological processes used throughout. Due to the inclusion of multiple peer-reviewed articles and the necessity for these to be comprehensible as stand-alone manuscripts, there is some content overlap between Chapters Two, Three, Four and Five.

Chapter One provides a brief outline of breaststroke swimming and defines the research aims of the project. The project is subsequently positioned within the field of elite breaststroke biomechanics in Chapter Two. Within Chapter Two the body of relevant existing literature is systematically collated and critically evaluated to synthesise the biomechanical factors influencing elite breaststroke swimming performance and establish the research areas in which there is limited understanding.

The three original research studies that were designed and conducted in response to identified gaps within the literature are detailed in Chapters Three, Four and Five. The original research study detailed in Chapter Three reports the temporal properties of elite breaststroke swimmers during competition. During this investigation performances of swimmers from 86 breaststroke races at 100 m and 200 m distances contested over three swimming seasons were analysed to explore the relationships between temporal patterns and breaststroke swimming performance.

The second original research study contained in this project is detailed in Chapter Four. This research study investigates technical solutions employed by elite breaststroke swimmers at 100 m pace through the description of associations between hand, knee and foot path, and swimming velocity. To quantify these associations estimates of the three-dimensional position of the hand, knee and foot were derived for eleven elite breaststroke swimmers and used to calculate the total distance travelled, maximum lateral position and relative lateral position of the hand, knee and foot throughout various phases of the stroke cycle. The associations of hand, knee and foot displacement characteristics, as well as hip velocity, were subsequently evaluated using correlational analysis.

The final original research article presented in this project is detailed in Chapter Five. This research article discusses the association of range of motion, dryland strength-power, anthropometry, and hip velocity in elite breaststroke swimmers. To establish associations between these parameters a series of range of motion, dryland strength (isometric adductor squeeze test), dryland power (maximal velocity pull up test and maximal height countermovement jump test), and anthropometric measures were assessed in 11 elite-level breaststroke specialists. Athlete performance across these parameters was then used to establish group-based averages and expected variance within an elite breaststroke population. Associations between dryland strength-power measures and propulsive velocity were subsequently evaluated using correlational analysis and second-order polynomial modelling.

Following presentation of the three original research studies that comprise this project, a supplementary methodological report is provided in Chapter Six. This chapter further details the three-dimensional video-based analysis methods described in Chapter Four and relates described methodology to the existing applied literature.

The final chapter of this project, Chapter Seven, summarises the key findings of each of the three original research studies and discusses the interrelatedness of subject areas. Throughout this chapter implications of the present project were identified to highlight how reported findings may be applied to improve and optimise the performance of elite breaststroke swimmers.

Chapter Two: Stroke Kinematics, Temporal Patterns, Neuromuscular Activity, Pacing and Kinetics in Elite Breaststroke Swimming: A Systematic Review

This chapter includes a published, co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:

Nicol, E., Pearson, S., Saxby, D., Minahan, C., & Tor, E. (2022). Stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics in elite breaststroke swimming: a systematic review. *Sports Medicine-Open*, *8*(1), 1-24.

My contribution to the paper involved the conception and design of the systematic review, collation and preliminary analysis of appropriate resources, analysis and interpretation of included resources, and manuscript preparation.

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Stroke Kinematics, Temporal Patterns, Neuromuscular Activity, Pacing and Kinetics in Elite Breaststroke Swimming: A Systematic Review

2.1 Abstract

Background: Breaststroke is a technically complex stroke characterised by discontinuous propulsive phases, large intracyclic velocity variation and low mean velocity. Performance of this stroke at an elite level is influenced by a number of biomechanical, physiological and psychological factors. The present systematic review aimed to synthesise the biomechanical factors influencing elite breaststroke swimming performance. This review aims to provide elite coaches and performance scientists with a breadth of knowledge from which training and racing interventions can be developed.

Methods: Electronic searches of Medline, Scopus and SPORTDiscus databases were conducted in May 2020 and March 2022. Search results that were peer-reviewed, published in English and published during or after the year 2000 were considered for review. The methodological rigour of studies was assessed using a risk of bias scale previously used for the evaluation of sports science research.

Results: Thirty-eight articles were included in the present review. Articles investigated elite breaststroke performance in relation to one of the following areas: stroke kinematics, temporal patterns, neuromuscular activity, pacing and kinetics.

Discussion: Kinematic, temporal and neuromuscular activity comparisons between groups of various race distance, performance or experience level, and athlete sex frequented the literature. These analyses demonstrated differences in stroke rate, stroke length, propulsive time, recovery time, glide time, sum of total integrated EMG and triceps brachii activation patterns between groups. The evaluation of various pacing strategies, and the relationship between kinetics and breaststroke performance was comparatively rare within the literature. Further research into the relationship between kinetics and breaststroke performance, and the manipulation of pacing strategy would increase the breadth of knowledge from which coaches and performance scientists can develop evidence-based training and racing interventions.

2.2 Background

Breaststroke is one of four competitive strokes contested at international swimming events. At the Olympic Games breaststroke is raced over 100 m and 200 m distances, while an additional 50 m event is contested at World Championships. Breaststroke swimming is constrained by several rules that outline permitted technique. As defined by the swimming governing body, Fédération Internationale De Natation (FINA):

1. After the start and after each turn, the swimmer may take one arm stroke completely back to the legs during which the swimmer may be submerged.
2. From the beginning of the first arm stroke after the start and after each turn, the body shall be on the breast. From the start and throughout the race the stroke cycle must be one arm stroke and one leg kick in that order. All movements of the arms shall be simultaneous and on the same horizontal plane without alternating movement.
3. The hands shall be pushed forward together from the breast on, under, or over the water. The elbows shall be under water except for the final stroke before the turn, during the turn and for the final stroke at the finish. The hands shall not be brought back beyond the hip line, except during the first stroke after the start and each turn.
4. During each complete cycle, some part of the swimmer's head must break the surface of the water. All movements of the legs shall be simultaneous and on the same horizontal plane without alternating movement.
5. The feet must be turned outwards during the propulsive part of the kick.
6. At each turn and at the finish of the race, the touch shall be made with both hands separated and simultaneously at, above, or below the water level (Féderation Internationale De Natation, 2017).

Technical rules result in several technique characteristics unique to breaststroke swimming. Dissimilar to other competitive strokes (backstroke, butterfly and freestyle) breaststroke is characterised by two discontinuous propulsive phases (Takagi et al., 2004) and high resistive drag forces that result from underwater limb recoveries (Leblanc et al., 2006). Due to these characteristics breaststroke swimming produces the lowest mean velocity and the highest level of intracyclic velocity variation among the competitive strokes (Gourgoulis et al., 2018).

Despite the technical constraints placed on athletes during breaststroke events, a level of variability based on temporal characteristics, coordination patterns, neuromuscular activity and pacing profiles is still possible between individuals. In addition to producing variability between athletes, each of these parameters are suggested to influence breaststroke swimming performance at an elite level. The multiplicity of parameters reported to influence breaststroke swimming performance makes the identification of optimal training and racing strategies difficult.

At present no review has been performed on the biomechanics of elite breaststroke swimming. The present review aims to address this gap within the literature to synthesise the biomechanical factors influencing elite breaststroke swimming performance. Findings of this review will be of benefit to swimming coaches and performance scientists in the development of training and racing interventions aimed at improving breaststroke swimming performance.

2.3 Methods

2.3.1 Search Strategy

Guidelines provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were followed in this review (Moher et al., 2010). A literature search was conducted in May 2020 across three electronic databases: Medline, Scopus and SPORTDiscus. Search filters were used to confine results to peer-reviewed articles published in English and published during or after the year 2000. Filters were used to ensure only recently published articles (preceding 20 years) from trusted sources were considered for review. A combination of the following search terms were used: “breaststroke”, “biomechanics”, “technique”, “style”, “elite”, “national”, “international”, “anthropometry”, “flexibility” and “strength”.

2.3.2 Selection Criteria

All search results were evaluated for eligibility using a number of criterion measures. Articles were excluded if (1) a full-text copy was unavailable, (2) the article was not original research ie. a review article, (3) the study was not conducted in a swimming pool environment, (4) breaststroke swimming was not investigated, (5) a non-elite or non-breaststroke sample was used, (6) a youth only sample was used or (7) biomechanics was not a primary area of investigation. Figure 2.1 illustrates the search screening process.

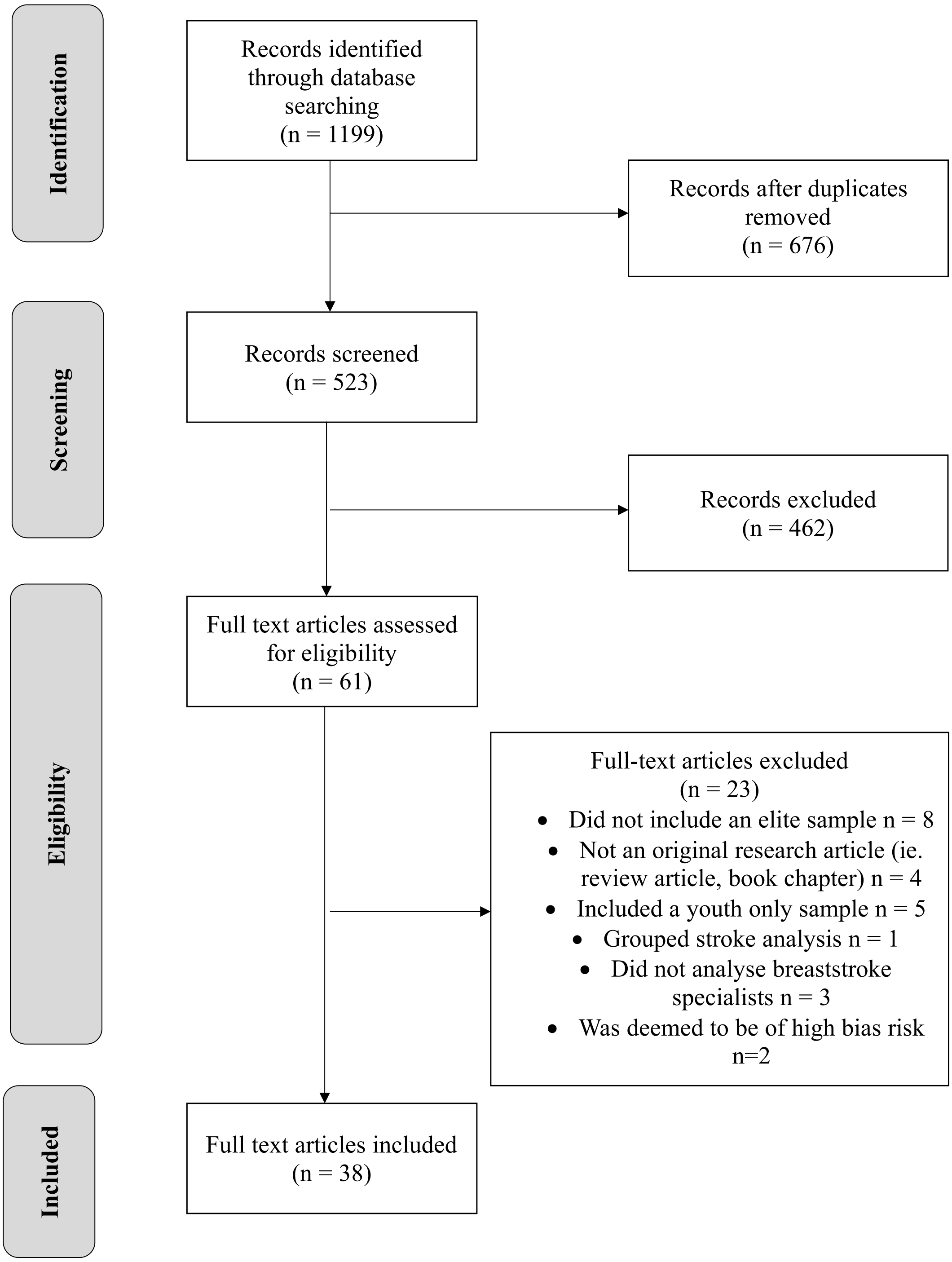

Figure 2.1 Search Screening Process Following PRISMA Guidelines

2.3.3 Quality Assessment

The quality of eligible studies was assessed using the risk of bias scale developed by Hindle et al. (2019a). This scale is based on other evaluation checklists and has previously been used for the assessment of sports research (Hindle et al., 2019b; Natera et al., 2020). Sixteen standards were used to evaluate article quality: three standards to study design, four standards to sample characteristics, four standards to methodology, and five standards to results and discussion. A detailed outline of assessment criteria is provided in Table 2.1. One point was awarded for each standard met to a maximum total of 16 points. No half points were awarded. Risk of bias score was subsequently determined using the total number of points awarded. Articles scored ≥11 points were categorised low bias risk. Articles scored 6-10 points were categorised satisfactory bias risk. Scores of <5 were categorised high bias risk. Only articles with a low or satisfactory bias risk were included in the present review.

Table 2.1 Quality Assessment Scale.

Element	Standard	Description
Study Design	1.1	The study design is clearly stated
	1.2	The objectives/purpose of the study is clearly defined
	1.3	The design of the study adequately tests the hypothesis
Sample Characteristics	2.1	The criteria for the inclusion of participants is clearly described
	2.2	The characteristics of the population are clearly described
	2.3	The study sample is representative of the population intended to the study
	2.4	A description of how the study size was arrived at is provided
Methodology	3.1	The testing methods are clearly described
	3.2	The measurement tools used are valid and reliable
	3.3	The statistical methods used well described
	3.4	The statistical tests used to analyse the data are appropriate
Results & Discussion	4.1	The results are well described
	4.2	The information provided in the paper is sufficient to allow a reader to make an unbiased assessment of the findings of the study
	4.3	Confounding factors are identified
	4.4	Sponsorships/ conflicts of interest are acknowledged
	4.5	Any limitations to the study are identified

2.4 Results

2.4.1 Study Characteristics

Following screening procedures and quality assessment, 38 articles were retained for review. Table 2.2 outlines publication details of articles contained within the present review. Of the 38 articles retained 19 were categorised low bias risk and 19 were categorised as satisfactory bias risk (Table 2.3).

The most commonly used method for data collection in the eligible articles was videography (n=15). An additional six studies used a combination of electromyography (EMG) and videography, six studies analysed retrospective race data and four studies used hand-timing or pacing technology throughout data collection. Other data collection methods included the use of a linear position transducer (otherwise referred to as a velocimeter or speedreel) and videography (n=3), accelerometry (n=1), force gauge (n=1), pressure sensors (n=1) and EMG without videography (n=1).

Table 2.2 Publication Details of Reviewed Articles.

Study	Author/s	Publication Year	Country	Journal
The Influence of Stroke Mechanics into Energy Cost of Elite Swimmers	Barbosa et al.	2008	Portugal	European Journal of Applied Physiology
Evaluation of Arm-Leg Coordination in Flat Breaststroke	Chollet et al.	2004	France	International Journal of Sports Medicine
Observation and Technical Characterisation in Swimming: 200m Breaststroke	Conceição et al.	2013	Portugal	Locomotor Apparatus in Exercise and Sports
Neuromuscular Fatigue During 200m Breaststroke	Conceição et al.	2014	Portugal	Journal of Sports Science and Medicine
Neuromuscular and Motor Patterns in Breaststroke Technique	Conceição et al.	2019	Portugal	Brazilian Journal of Kineanthropometry & Human Performance
Analysis of Speed, Stroke Rate, an Stroke Distance for World-Class Breaststroke Swimming	Garland Fritzdorf et al.	2009	Denmark	Journal of Sports Sciences
Differences Between Elite and Sub-Elite Swimmers in a 100 m Breaststroke: A New Race Analysis Approach with Time-Series Velocity Data	Gonjo and Olstad	2021	Norway	Sports Biomechanics
Difference Muscle Recruitment Strategies Among Elite Breaststrokers	Guignard et al.	2015	France	International Journal of Sports Physiology and Performance

Kinematic Measures and Stroke Rate Variability in Elite Female 200m Swimmers in the Four Swimming Techniques: Athens 2004 Olympic Semi-finalists and French National 2004 Championship Semi-finalists	Hellard et al.	2008	France	Journal of Sports Sciences
Relationships Between Swimming Style and Dry-Land Strength in Breaststroke	Invernizzi et al.	2014	Italy	Sports Sciences for Health
Do Qualitative Changes in Interlimb Coordination Lead to Effectiveness of Aquatic Locomotion Rather than Efficiency?	Komar et al.	2014	France	Journal of Applied Biomechanics
Arm-Leg Coordination in Flat Breaststroke: A Comparative Study Between Elite and Non-Elite Swimmers	Leblanc et al.	2005	France	International Journal of Sports Medicine
Intra-cyclic Distance Per Stroke Phase, Velocity Fluctuations and Acceleration Time Ratio of a Breaststroker's Hip: A comparison Between Elite and Non Elite Swimmers at Different Race Paces	Leblanc et al.	2006	France	International Journal of Sports Medicine
Stability of Behaviour Patterns in the 200m Breaststroke	Louro et al.	2016	Portugal	Brazilian Journal of Kineanthropometry & Human Performance
Relationship Between Tethered Forces and the Four Swimming Technique Performances	Morouço et al.	2011	Portugal	Journal of Applied Biomechanics
The Temporal Analysis of Elite Breaststroke Swimming During Competition	Nicol et al.	2021	Australia	Sports Biomechanics
Muscle Activation in World-Champion, World-Class and National Breaststroke Swimmers	Olstad et al.	2017a	Norway	International Journal of Sports Physiology and Performance
Muscular Coordination, Activation and Kinematics of World-Class and Elite Breaststroke Swimmers During Submaximal and Maximal Efforts	Olstad et al.	2017b	Norway	Journal of Sports Sciences

Key Factors Related to Short Course 100 m Breaststroke Performance	Olstad et al.	2020	Norway	International Journal of Environmental Research and Public Health
Changes in Kinematics and Arm-Leg Coordination During a 100m Breaststroke Swim	Oxford et al.	2017	UK	Journal of Sports Sciences
Analysis of Selected Kinematic and Physiological Performance Determinants During Incremental Testing in Elite Swimmers	Psycharakis et al.	2008	UK	Journal of Strength and Conditioning Research
Analysis of Lap Times in International Swimming Competitions	Robertson et al.	2009	Australia	Journal of Sports Sciences
An Approach to Identifying the Effect of Asymmetries on Body Alignment in Swimming Exemplified by a Case Study of a Breaststroke Swimmer	Sanders et al.	2015	Australia	Journal of Sports Science and Medicine
A New Index of Flat Breaststroke Propulsion: A Comparison of Elite Men and Women	Seifert and Chollet	2005	France	Journal of Sports Sciences
Modelling Spatial-Temporal and Coordinative Parameters in Swimming	Seifert and Chollet	2009	France	Journal of Science and Medicine in Sport
Interlimb Coordination and Energy Cost in Swimming	Seifert et al.	2013	France	Journal of Science and Medicine in Sport
Coordination Pattern Adaptability: Energy Cost of Degenerate Behaviours	Seifert et al.	2014	France	PLoS One
Reproducibility of Pacing Profiles in Elite Swimmers	Skorski et al.	2014	Germany	International Journal of Sports Physiology and Performance

Accelerometer Profile of Motion of the Pelvic Girdle in Breaststroke Swimming	Staniak et al.	2016	Poland	Journal of Human Kinetics
Differences in Stroke Phases, Arm-Leg Coordination and Velocity Fluctuation due to Event, Gender and Performance Level in Breaststroke	Takagi et al.	2004	Japan	Sports Biomechanics
An Analysis of Selected Kinematic Variables in National and Elite Male and Female 100m and 200m Breaststroke Swimmers	Thompson et al.	2000	UK	Journal of Sports Sciences
The Effect of Even, Positive and Negative Pacing on Metabolic, Kinematic and Temporal Variables During Breaststroke Swimming	Thompson et al.	2003	UK	European Journal of Applied Physiology
A Comparison of Selected Kinematic Variables Between Races in National and Elite Male 200m Breaststroke Swimmers	Thompson et al.	2004a	UK	Journal of Swimming Research
The Effects of Changing Pace on Metabolism and Stroke Characteristics During High-Speed Breaststroke Swimming	Thompson et al.	2004b	UK	Journal of Sports Sciences
Use of Pressure Distribution Analysis to Estimate Fluid Forces Around a Foot During Breaststroke Kicking	Tsunokawa et al.	2015	Japan	Sports Engineering
Muscle Coordination During Breaststroke Swimming: Comparison Between Elite Swimmers and Beginners	Vaz et al.	2016	Portugal	Journal of Sports Sciences
Sex-Related Differences and Age of Peak Performance in Breaststroke Versus Freestyle Swimming	Wolfrum et al.	2013	Switzerland	BMC Sports Science, Medicine and Rehabilitation
Changes in Breaststroke Swimming Performances in National and International Athletes Competing Between 1994 and 2011: A Comparison with Swimming Performances	Wolfrum et al.	2014	Switzerland	BMC Sports Science, Medicine and Rehabilitation

Table 2.3 Quality Assessment of Reviewed and Excluded Articles.

Study	Publication Year	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4	4.5	Total
Barbosa et al.	2008	*	*			*			*	*	*	*	*	*				9
Chollet et al.	2004	*	*			*			*		*	*	*	*				8
Conceição et al.	2013	*	*			*	*		*		*	*	*	*		*		10
Conceição et al.	2014	*	*	*		*			*		*	*	*	*				9
Conceição et al.	2019	*	*			*			*				*	*		*		7
Garland Fritzdorf et al.	2009	*	*		*		*						*				*	6
Gonjo and Olstad	2021	*	*	*		*			*	*	*	*	*	*	*	*	*	13
Guignard et al.	2015	*	*			*				*	*	*		*				7
Hellard et al.	2008	*	*	*	*	*	*		*	*	*	*	*	*		*		13
Invernizzi et al	2014	*	*			*	*		*	*	*	*	*	*	*	*		12
Komar et al.	2014	*	*	*		*			*	*	*	*	*	*		*	*	12
Leblanc et al.	2005	*	*			*			*		*	*	*	*				8
Leblanc et al.	2006	*	*	*					*	*	*	*	*	*				9
Louro et al.	2016	*	*	*		*			*	*							*	7
Morouço et al.	2011	*	*		*	*			*		*	*	*	*	*			10
Nicol et al.	2021	*	*	*		*	*		*	*	*	*	*	*		*		12
Olstad et al.	2017a	*	*	*		*			*	*	*	*	*	*			*	11
Olstad et al.	2017b	*	*			*			*	*	*	*	*	*		*	*	11
Olstad et al.	2020	*	*	*		*	*		*	*	*	*	*	*		*	*	13
Oxford et al.	2017	*	*	*	*	*			*	*	*	*	*	*	*	*		13
Psycharakis et al.	2008	*	*		*	*		*	*	*	*	*	*	*		*	*	13
Robertson et al.	2009	*	*				*		*	*	*	*	*	*	*		*	11
Sanders et al.	2015	*	*		*	*		*	*	*	*	*	*	*				11

Seifert and Chollet	2005	*	*	*		*			*		*	*	*	*				9
Seifert and Chollet	2009	*	*			*	*		*	*	*	*	*	*	*			11
Seifert et al.	2014	*	*	*		*			*	*	*	*	*	*		*		11
Seifert et al.	2013	*	*	*		*			*	*	*	*	*	*		*		11
Skorski et al.	2014	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	15
Staniak et al.	2016	*	*			*			*	*	*	*	*	*		*		10
Takagi et al.	2004	*	*		*			*	*		*	*	*	*	*			10
Thompson et al.	2000	*	*				*		*		*	*	*	*				8
Thompson et al.	2003	*	*			*			*	*	*	*	*	*			*	10
Thompson et al.	2004a	*	*		*		*		*		*	*	*	*			*	10
Thompson et al.	2004b	*	*			*			*		*	*	*	*				8
Tsunokawa et al.	2015	*	*			*			*	*	*		*	*		*	*	10
Vaz et al.	2016	*	*	*		*			*		*	*	*	*	*	*	*	12
Ward	2018	*	*		*						*	*						5
Wolfrum et al.	2013	*	*	*			*	*	*	*	*	*	*	*	*	*	*	14
Wolfrum et al.	2014	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*	15
Xin-Feng et al.	2007	*	*						*				*	*				5

**Note*. refer to Table 2.1 for criterion definitions.

2.4.2 Videography

A total of 24 studies used videography throughout data collection. Fifteen of these studies used videography as the sole method of data collection. Videography-based studies used between one and 11 cameras during data collection. Table 2.4 provides further details regarding the methodology used and themes discussed throughout each of the 15 exclusively videography-based studies. The majority of these studies analysed breaststroke swimming in two-dimensions (2D) (n=12). All studies that conducted 2D analysis of breaststroke swimming investigated temporal and kinematics characteristics of breaststroke swimming within an elite population. Group comparisons based on race distance, experience level and sex were frequently discussed within 2D videography studies.

The remaining three videography studies analysed breaststroke swimming in three-dimensions (3D). The comparatively small number of studies that used 3D methodology may be attributed to the time-consuming and resource-demanding procedures required of this method (Dadashi et al., 2013; Monnet et al., 2014). Each of these three 3D-based studies had different aims and procedures, however met these aims through the investigation of similar parameters (acceleration, displacement, angular velocity and joint angles) (Table 2.4).

Table 2.4 Outline of Videography Studies.

Study	Publication Year	Themes	Number of Participants	Speed of Swimming	Number of Cameras Used	Dimensionality of Analysis	Type of Camera Set Up (Above- or Below-Water)	Parameters Measured
Gonjo and Olstad	2021	Kinematics Experience level comparison	7 elite male swimmers 7 sub-elite male swimmers	Time trial	10	2D	Above- and below-water	Velocity Race segment analysis
Hellard et al.	2008	Kinematics Experience level comparison	16 female international-level semi-finalists 16 female national-level semi-finalists	In competition	4	2D	Above-water	Stroke rate Stroke length Velocity
Invernizzi et al.	2014	Strength expression	24 male national-level swimmers 20 female national-level swimmers	Time trial	1	2D	NA	Stroke rate Stroke length Velocity Normalised chin-up score Normalised jump-reach score
Komar et al.	2014	Temporal analysis Experience level comparison	5 male expert swimmers 3 female expert swimmers 6 male recreational swimmers 4 female recreational swimmers	Race pace simulation	6	3D	Above- and below-water	Velocity Intracyclic velocity variation Displacement Acceleration Elbow angle Knee angle
Louro et al.	2016	Temporal analysis Individual analysis	5 male national-level swimmers	Time trial	2	2D	Above- and below-water	Movement events Stroke phases
Olstad et al.	2020	Kinematics	15 male high-level swimmers	Time trial	11	2D	Above- and below-water	Velocity Race segments analysis Stroke rate Stroke length Glide distance Stroke count
Oxford et al.	2017	Kinematics Temporal analysis	18 male national-level swimmers	Time trial	3	2D	Below-water	Stroke rate Stroke length

			8 female national-level swimmers					Velocity La^+ Heart rate RPE Stroke phases
Sanders et al.	2015	Kinematics Asymmetry	1 elite female swimmer	Fatigue set	6	3D	Above- and below-water	Displacement Acceleration Angular velocity Peak torque
Seifert and Chollet	2005	Temporal analysis Race distance comparison Sex comparison	9 elite male swimmers 8 elite female swimmers	Race pace simulation	3	2D	Above- and below-water	Stroke rate Stroke length Velocity Index of flat breaststroke propulsion Stroke phases
Seifert and Chollet	2009	Temporal analysis Race distance comparison	12 elite male swimmers	Race pace simulation	4	2D	Above- and below-water	Stroke rate Stroke length Velocity Stroke phases
Seifert et al.	2013	Coordination pattern manipulation Energy cost	8 male national-level swimmers	Submaximal	2	2D	Below-water	Stroke rate Stroke length VO_2 La^+
Seifert et al.	2014	Coordination pattern manipulation Energy cost	7 national-level swimmers [a]	Submaximal	6	3D	Above- and below-water	VO_2 La^+ Energy cost Intracyclic velocity variation Angular velocity Trunk inclination Elbow angle Knee angle Stroke phases

Takagi et al.	2004	Temporal analysis Race distance comparison Experience level comparison	15 male 50 m international races 16 male 100 m international races 15 male 200 m international races 12 female 50 m international races 10 female 100 m international races 13 female 200 m international races	In competition	3	2D	Below-water	Stroke rate Stroke length Velocity Intracyclic velocity variation Stroke phases
Thompson et al.	2000	Kinematics Race distance comparison	159 male 100 m international- or national-level finals 158 female 100 m international- or national-level finals 159 male 200 m international- or national-level finals 158 female 200 m international- or national-level finals	In competition	5	2D	Above-water	Stroke rate Stroke length Velocity Skill time
Thompson et al.	2004a	Kinematics Individual between race comparison	36 male international- or national-level finalists	In competition	5	2D	Above-water	Stroke rate Stroke length Velocity Skill time

[a] Participant sex not specified.

2.4.3 Electromyography Methods

Seven studies used EMG during data collection. All studies with the exception of Guignard et al. (2015) combined EMG analysis with videography. EMG-based studies involved the fixation of bipolar surface electrodes (n=4) or triode surface electrodes (n=3) to the skin surface directly above various muscle groups for the measurement of neuromuscular activity. All EMG-based studies collected neuromuscular information wirelessly, and all sampled at 1000 Hz. EMG studies investigated the activation patterns of the following eight muscles: biceps brachii, pectoralis major, trapezius, triceps brachii, bicep femoris, gastrocnemius, rectus femoris and tibialis anterior. Table 2.5 details the methods used and themes discussed within each of the seven EMG-based studies. The analysis of neuromuscular activity was frequently combined with a kinematic analysis from videography. Group comparisons based on experience level were frequently made and discussed.

Table 2.5 Outline of EMG Studies.

Study	Publication Year	Themes	Number of Participants	Speed of Swimming	Number of EMG Sensors Used	Location of EMG Sensors	Number of Cameras Used	Dimensionality of Analysis	Parameters Measured
Conceição et al.	2013	Neuromuscular activity Kinematics	12 male national-level swimmers	Time trial	4	Biceps brachii Deltoid anterior Pectoralis major Triceps brachii	2	2D	Stroke rate Stroke length Velocity La^+
Conceição et al.	2014	Fatigue Neuromuscular activity Kinematics	9 male national-level swimmers	Time trial	4	Biceps brachii Deltoid anterior Pectoralis major Triceps brachii	2	2D	Stroke rate Stroke length Velocity La^+ Stroke index
Conceição et al.	2019	Neuromuscular activity Temporal patterns	5 male national-level swimmers	Time trial	4	Biceps brachii Deltoid anterior Pectoralis major Triceps brachii	2	2D	Temporal patterns Body undulation
Guignard et al.	2015	Neuromuscular activity Individual analysis	1 female international-level swimmers 2 female national-level swimmers	Race pace simulation	4	Bicep femoris Gastrocnemius Rectus femoris Tibialis anterior	NA	NA	Knee angle Ankle angle Thigh angle Stroke phases
Olstad et al.	2017a	Neuromuscular activity Temporal analysis Experience level comparison	2 world-class male swimmers 2 national-elite male swimmers 2 world-class female swimmers 2 national-elite female swimmers	Race pace simulation	8	Biceps brachii Pectoralis major Trapezius Triceps brachii Bicep femoris Gastrocnemius Rectus femoris Tibialis anterior	6	3D	Stroke rate Stroke length Velocity Knee angle Maximal voluntary contraction Stroke phases

Olstad et al.	2017b	Neuromuscular activity Kinematics Intensity differences	4 elite male swimmers 5 elite female swimmers	Race pace simulation	8	Biceps brachii Pectoralis major Trapezius Triceps brachii Bicep femoris Gastrocnemius Rectus femoris Tibialis anterior	16	3D	Stroke rate Stroke length Velocity Knee angle Maximal voluntary contraction Stroke phases
Vaz et al.	2016	Neuromuscular activity Experience level comparison	4 elite male swimmers 4 elite female swimmers 4 beginner male swimmers 4 beginner female swimmers	Race pace simulation	8	Biceps brachii Pectoralis major Trapezius Triceps brachii Bicep femoris Gastrocnemius Rectus femoris Tibialis anterior	6	2D	Knee angle Stroke phases

2.4.4 Retrospective Race Data Methods

Six studies used retrospective competition data for the analysis of elite breaststroke swimming. This approach required the collation and analysis of existing competition splits, times, metadata and race footage. The number and level of analysed competitions is detailed in Table 2.6. Total race and split times were typically used to determine pacing profiles and race speed characteristics. Three studies used this information to make between-group comparisons based on sex, age and/or experience level. Two studies used pacing and speed data to compare individual results between competitions. The final study to use retrospective race footage to calculate the amount of time spent in various stroke phases and determine temporal differences between-groups based on race distance and sex.

Table 2.6 Outline of Retrospective Race Data Studies.

Study	Publication Year	Themes	Number of Races Analysed	Level & Date Range of Competition	Parameters Measured
Garland Fritzdorf et al.	2009	Effective work per stroke Individual race comparison	14 male 100 m breaststroke races. 7 races of various world ranked swimmers and 7 races of a single world ranked swimmer	NA	Total race time Split time Effective work per stroke
Nicol et al.	2021	Temporal analysis Race distance comparison Sex comparison	20 male 100 m national-level races 15 male 200 m national-level races 24 female 100 m national-level races 27 female 200 m national-level races	National and international level competitions over a 3 year period	Stroke phase time Total race time
Robertson et al.	2009	Pacing Stroke comparison Experience level comparison	1530 male races [a,b] 1527 female races [a,b]	9 international level competitions over a 7 year period	Total race time Split time Race position
Skorski et al.	2014	Pacing Individual race comparison	362 male races from 158 male athletes [a] 70 male 200 m breaststroke races	22 national and international level competitions over a 1 year period	Total race time Split time Average velocity
Wolfrum et al.	2013	Sex comparison Experience level comparison Age group comparison Race speed	14166 Swiss female races [a,b] 14798 Swiss male races [a,b] 240 international-level female races [a,b] 240 international-level male races [a,b]	Swiss athletes: national level competition over a 4 year period International athletes: NA	Average swimming speed
Wolfrum et al.	2014	Sex comparison Race speed	NA	Swiss athletes: best performances of the top 10 Swiss male and female athletes over a 17 year period International athletes: 8 international level competitions over a 17 years period	Average swimming speed

[a] Multiple strokes analysed.

[b] Number of breaststroke races analysed unspecified.

2.4.5 Other Analysis Methods

The following data collection methods were used by fewer than four studies within the dataset: linear position transducer with videography (n=3), pacing lights (n=3), force gauge (n=1), hand timing (n=1), accelerometers (n=1) and pressure sensors (n=1). Themes of discussion varied widely between these studies. Table 2.7 outlines the samples used and themes discussed within each of these studies.

Table 2.7 Outline of Studies with Unique Methodology.

Study	Publication Year	Themes	Number of Participants	Speed of Swimming	Methodology Used	Methodology Details	Parameters Measured
Barbosa et al.	2008	Kinematics Energy Cost	3 international-level male swimmers 2 international-level female swimmers	Submaximal	Pacing lights		Stroke rate Stroke length Velocity VO_2 La^+ Energy cost Energy expenditure
Chollet et al.	2004	Temporal analysis Race distance comparison	9 male expert swimmers 7 female expert swimmers	Race pace simulation	Linear position transducer & videography	3 cameras used for 2D videography analysis	Stroke rate Stroke length Velocity Stroke phases
Leblanc et al.	2005	Temporal analysis Race distance comparison Experience level comparison	11 national- and international-level male swimmers 9 national- and international-level female swimmers 11 regional-level male swimmers 9 regional-level female swimmers	Race pace simulation	Linear position transducer & videography	3 cameras used for 2D videography analysis	Stroke rate Stroke length Velocity Stroke phases
Leblanc et al.	2007	Temporal analysis Kinematics Experience level comparison	9 national-level male swimmers 9 regional-level male swimmers	Race pace simulation	Linear position transducer & videography	3 cameras used for 2D videography analysis	Stroke rate Stroke length Velocity Intracyclic velocity variation Acceleration-deceleration time ratio Stroke phases
Morouço et al.	2011	Force Velocity	8 international-level female swimmers	Race pace simulation	Force gauge	Load cell attached to a steel cable and affixed to a belt worn around participants' waist	Velocity Force Height Weight

							Hydrostatic mass Surface area
Psycharakis et al.	2008	Kinematics Fatigue Physiology	2 international-level male swimmers 2 international-level female swimmers	Submaximal	Hand timing		Stroke rate Stroke length Velocity La^+
Staniak et al.	2016	Accelerometry Temporal analysis	5 elite male swimmers	Submaximal	Accelerometry	1 accelerometer positioned on dorsally on the pelvic girdle	Acceleration Angular velocity Stroke phases
Thompson et al.	2004b	Kinematics Physiology Pacing	9 national-level male swimmers	Time trial	Aquapacer™		Stroke rate Stroke count VO_2 La^+ Heart rate Rate of perceived exertion Height Weight Skinfolds Hydrostatic mass
Thompson et al.	2003	Kinematics Physiology Pacing	9 national-level male swimmers	Time trial	Aquapacer™		Stroke rate Stroke count VO_2 La^+ Heart rate Rate of perceived exertion Height Weight Skinfolds
Tsunokawa et al.	2015	Fluid force Velocity	8 national-level male swimmers	Race pace simulation	Pressure sensors	8 sensors positioned on the foot	Force Fluid force Impulse

2.5 Discussion

A multitude of factors have been reported to influence breaststroke technique and performance at an elite level. Within the existing literature a number of themes are frequently discussed. These include temporal characteristics, stroke kinematics, neuromuscular activity, pacing and kinetics. The following section will discuss each theme with reference to the existing literature.

2.5.1 Stroke Kinematics

Average horizontal velocity, measured by the time to cover a given distance, is the primary outcome measure used to assess swimming competition performance. Kinematic parameters referenced within the swimming biomechanics literature are consequently described in relation to their influence on swimming velocity. Table 2.8 details the average velocity values reported within each reviewed study where available. Two of the most frequently referenced kinematic parameters in breaststroke swimming biomechanics are stroke rate (SR) and stroke length (SL).

Stroke kinematic characteristics including SR and SL vary by race distance and race duration. The 100 m event is characterised by higher mean SR and lower mean SL when compared to the 200 m event (Leblanc et al., 2006; Takagi et al., 2004; Thompson et al., 2000). This pattern is consistent during various intensity efforts, with increases to SR and decreases to SL associated with increasing intensity (Olstad, Vaz, et al., 2017). Stroke kinematics have also been reported to change over the duration of an event, however the reported direction of these changes is inconsistent. Whilst SR decreases over the duration of a 100 m event have been reported during short course (25 m pool) efforts (Olstad et al., 2020; Oxford et al., 2017) , SR increases over the duration of a 100 m event have been reported in long course (50 m pool) efforts (Thompson et al., 2000). Discrepancy in the reported direction of SR and SL changes over a 100 m event may be attributed to variance in the methods used to calculate SR between studies (Table 2.8) or a difference in race profiles between short course and long course events. An increase in SR across race duration is also reported to occur during the long-course 200 m event when comparing first and second 100 m sections. An increase in SR over the latter part of a long-course 100 m or 200 m event is suggested to be a compensatory strategy for SL reduction (Thompson et al., 2000; Thompson, MacLaren, et al., 2004). Reduction in velocity over the final 50 m of a 100 m event irrespective of an increase in SR suggests that SR increases are not sufficient to overcome the effects of decreased SL (Thompson et al., 2000).

Stroke kinematics also vary according to a number of fixed and modifiable athlete characteristics. One such characteristic is the sex of the athlete. Male swimmers typically have a longer stroke length than females swimmers at 100 m and 200 m race distances (Oxford et al., 2017; Takagi et al., 2004). This sex-related difference is attributed to the greater height of male swimmers when compared to female swimmers (Seifert & Chollet, 2005). Elite male swimmers also maintain a higher average velocity than female swimmers across all race distances (Oxford et al., 2017; Wolfrum et al., 2013; Wolfrum et al., 2014). The magnitude of sex-related velocity differences however decreases with increasing race distance (Wolfrum et al., 2013; Wolfrum et al., 2014). This observation has been attributed to a greater swimming efficiency in female swimmers when compared to male swimmers (Wolfrum et al., 2014). Meaningful sex-related differences in SR are yet to be established. A modifiable athlete characteristic, muscular strength, is also said to influence stroke kinematics. Invernizzi et al. (2014) reported swimmers who achieved a high countermovement movement jump score adopted a stroke with high SL. Conversely, swimmers who scored highly on an exhaustive chin up test adopted a stroke with higher SR. Results from Invernizzi et al. (2014) suggest individuals adopt a SR to SL ratio based on their strength attributes. This suggestion is consistent with much of the existing literature that suggests optimal SR to SL ratios are best determined on an individual basis (Olstad et al., 2020; Psycharakis et al., 2008; Thompson et al., 2000; Thompson, Haljand, et al., 2004) with consideration of athlete anthropometry, technique, flexibility and coordination (Psycharakis et al., 2008). The individualised nature of optimal SR to SL ratios may also explain the weak and inconsistent relationships between these kinematic parameters and swimming velocity in cross-sectional group analyses.

As well as their use as descriptive measures to assess breaststroke swimming, SR and SL have also been used to assess stroke efficiency. Defined as an athlete’s ability to travel at a specified velocity with the fewest number of strokes, breaststroke efficiency may be assessed using stroke index (SI) (Equation 2.1) (Conceição et al., 2014; Costill et al., 1985)

$SI = average\ velocity * SL$ (2.1)

Higher values of SI indicate greater mechanical efficiency. This measure of mechanical efficiency assumes that the swimmer with the greatest stroke length at a given velocity has the best mechanical efficiency (Costill et al., 1985). As it is understood that optimal SR and SL ratios exist for individuals, stroke index may consequently be better used to assess intraindividual efficiency patterns rather than as a method of efficiency comparison between athletes. Despite this assumption common patterns in SI based on sex and race distance have been identified. Male swimmers typically have a higher SI when compared to female swimmers (Oxford et al., 2017). According to the SI model this finding would suggest that male swimmers swim with greater efficiency than female swimmers. The higher SI in male swimmers may instead reflect male-specific velocity and SL patterns rather than superior efficiency given that female swimmers have been reported to maintain higher swimming efficiency due body morphology differences (Wolfrum et al., 2014). This highlights a delimitation of SI as a method of intra-athlete efficiency comparison.

Over the course of a 200 m event, stroke efficiency (assessed using SI) has been reported to decrease (3.07 ± 0.25 m^2/s – 2.19 ± 0.29 m^2/s) (Conceição et al., 2014). The reduction in SI reflects reported kinematic changes to SL and swimming velocity that occur as race duration increases.

Another method used to assess breaststroke efficiency is intracyclic velocity variation (IVV). Quantified using time-velocity information IVV is calculated using equation 2.2 (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014).

$IVV = \frac{(MaxL - MinL) + (MaxA - MinT)}{V}$ (2.2)

Where MaxL corresponds to the maximum velocity achieved during the leg propulsion phase, MinL corresponds to the minimum velocity achieved during maximal knee flexion, MaxA corresponds to the maximum velocity achieved during the arm propulsive phase and MinT corresponds to the minimum velocity achieved during body glide (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014). Variations of this formula have been used by various research groups for similar stroke assessment (Leblanc et al., 2006).

Large IVV values are theoretically considered disadvantageous to swimming performance (Staniak et al., 2016). This theoretical perspective is grounded in the application of principle that there is a need to overcome higher inertial forces following large decelerations to initiate acceleration throughout subsequent propulsive phases (Leblanc et al., 2005; Seifert, Komar, Crettenand, & Millet, 2014). Applicability of this theoretical perspective to breaststroke swimming in currently unclear, following a comparison of stroke kinematics in elite and non-elite breaststroke swimmers reported that elite breaststroke swimmers had higher intracyclic velocity variation values than non-elite breaststroke swimmers (Leblanc et al., 2006). This observation was attributed to a need for the elite cohort to increase peak speed throughout the propulsive phases of the stroke in effort to increase average velocity across the stroke cycle as they were subject to the same constraints throughout the recovery phase of the stroke (Leblanc et al., 2006). As an alternative attribution, higher intracyclic velocity variation values of the elite cohort were suggested to result from an increased ability for this group to use added mass of water to counteract drag throughout deceleration phases of the stroke (Leblanc et al., 2006). The influence of added mass on velocity profiles in elite breaststroke swimmers warrants further research investigation to better understand this relationship, and to understand why theoretical perspectives may not consistently apply in elite breaststroke swimming.

Effective work per stroke (eWPS) is an additional method that has been used to calculate and assess stroke effectiveness in breaststroke swimming (equation 2.3) (Garland Fritzdorf et al., 2009).

$$eWPS\ (\%) = 100\left(\frac{V_i - V_m}{V_m}\right) \quad (2.3)$$

Where V_i are achieved speed values and V_m are modelled or expected speed values. Although eWPS has been associated with changes in mean race speed, and flatter effectiveness profiles with faster overall race time, this method of analysis is limited due to its assumption that effectiveness remains stable as SR changes (Garland Fritzdorf et al., 2009). It is also limited in its assumption that drag levels experienced by an individual remain constant across various speeds (Garland Fritzdorf et al., 2009). Effective work per stroke is consequently infrequently reported within the literature.

Stroke kinematics have also been associated with physiological cost. Changes to both SR and SL are associated with changes in energetics in breaststroke swimming (Barbosa, Fernandes, Keskinen, et al., 2008). Increases in SR are associated with an increase in energy cost (R^2 = 0.17, $p < .05$) (Barbosa, Fernandes, Keskinen, et al., 2008). Conversely, increases in SL are associated with decreased energy cost (R^2 = 0.24, $p < .05$) (Barbosa, Fernandes, Keskinen, et al., 2008). Despite weakness in the associations between SR, SL and energy cost, changes to SR and SL account for 53% and 40% of variance in energy cost respectively (Barbosa, Fernandes, Keskinen, et al., 2008).

Table 2.8 Stroke Rate, Stroke Length and Average Velocity Reported Ranges and Calculation Methods.

Study	Publication Year	Swimming Pace	SR Calculation (strokes per min)	Reported SR Range	SL Calculation (m per stroke)	Reported SL Range	Reported v (m/s)
Barbosa et al.	2008	Submaximal	Stopwatch measure over three stroke cycles.	NA	v/SR	NA	NA
Conceição et al.	2013	200 m	[a]	Male: 34.40 ± 3.58 – 37.52	[a]	Male: 1.96 ± 0.24 – 2.32 ± 0.37	Male: 1.16 ± 0.09 – 1.41 ± 0.07
Conceição et al.	2014	200 m	1/Stroke cycle length	Male: 34.80 ± 2.83 – 37.58 ± 4.90	[a]	Male: 1.92 ± 0.15 – 2.23 ± 0.18	Male: 1.14 ± 0.08 – 1.38 ± 0.09
Hellard et al.	2008	200 m	60/stroke duration	Male: 35.7 ± 3.1 – 37.9 ± 4.2	v/SR/60	Male: 1.94 ± 0.17 – 2.18 ± 0.26	Male: 1.18 ± 0.02 – 1.33 ± 0.02
Komar et al.	2014	70% and 90% of maximal speed	NA	NA	[a]	Male and female: 1.81 ± 0.33 – 2.78 ± 0.31	Male and female: 1.08 ± 0.11 – 1.37 ± 0.10
Leblanc et al.	2007	50 m, 100 m and 200 m	Stopwatch measure over three stroke cycles.	Male: 39.22 ± 3.23 – 51.91 ± 5.21	[a]	Male: 1.80 ± 0.26 – 2.15 ± 0.18	Male: 1.40 ± 0.10 – 1.53 ± 0.12
Olstad et al.	2017b	60%, 80% and 100% of maximal speed	[a]	Male and female: 32.20 ± 3.43 – 42.58 ± 4.36	[a]	Male and female: 1.70 ± 0.17 – 1.90 ± 0.21	Male and female: 1.04 ± 0.13 – 1.20 ± 0.16

Olstad et al.	2020	100m	[a]	Male: 49.62 ± 4.04 – 53.28 ± 4.01	[a]	Male: 1.58 ± 0.13 – 1.71 ± 0.11	Male: 1.32 ± 0.06 – 1.51 ± 0.07
Oxford et al.	2017	100 m	[a]	Male: 43.7 ± 5.6 – 46.8 ± 7.4 Female: 47.2 ± 8.4 – 49.7 ± 8.2	[a]	Male: 1.55 ± 0.24 – 1.64 ± 0.22 Female: 1.28 ± 0.22 – 1.39 ± 0.24	Male: 1.13 ± 0.07 – 1.24 ± 0.1 Female: 1.00 ± 0.08 – 1.11 ± 0.06
Psycharakis et al.	2008	Submaximal	Stopwatch measure over three stroke cycles.	NA	v/SR	NA	NA
Thompson et al.	2000	100 m and 200 m	Number of frames taken to complete a single stroke cycle immediately following the 25 m mark.	Male 100: 49.2 ± 5.4 – 51.0 ± 5.2 Female 100: 49.5 ± 5.8 – 49.7 ± 5.7 Male 200: 37.1 ± 4.5 – 43.0 ± 5.9 Female 200: 38.8 ± 5.3 – 43.4 ± 5.7	v/SR	Male 100: 1.67 ± 0.17 – 1.85 ± 0.30 Female 100: 1.52 ± 0.18 – 1.63 ± 0.19 Male 200: 1.84 ± 0.25 – 2.22 ± 0.25 Female 200: 1.66 ± 0.21 – 1.89 ± 0.25	Male 100: 1.40 ± 0.06 – 1.49 ± 0.05 Female 100: 1.24 ± 0.07 – 1.33 ± 0.07 Male 200: 1.31 ± 0.12 – 1.41 ± 0.07 Female 200: 1.18 ± 0.06 – 1.27 ± 0.07
Thompson et al.	2004a	200 m	[a]	Male: 37.03 ± 4.38 – 43.26 ± 4.28	v/SR	Male: 1.88 ± 0.19 – 2.28 ± 0.23	Male:1.34 ± 0.05 – 1.46 ± 0.05

[a] Calculation method unclear.

2.5.2 Temporal Analysis

2.5.2.1 Breaststroke Phase Models

Temporal analysis was often discussed with reference to stroke phases and/or coordination patterns. The stroke cycle is commonly described in two broad phases: pull and kick. Within each phase a number of subphases were described based on observable movement patterns. Table 2.9 outlines various stroke phase models used within the existing literature. The number of subphases described in each model varied between five and ten. Phase number discrepancy resulted from selection of different points within the stroke cycle to denote the beginning and ending of each phase. The separation or amalgamation of subphases most commonly occurred during the propulsive and recovery phases. Further phase reductions were observed in models that did not consider pull and kick glide phases in their model.

2.5.2.2 Between-Group Comparison Based on Race Distance

Between-group differences in temporal patterns were frequently discussed within the literature. Temporal differences were associated with variations in race distance, experience level and sex. Comparison of temporal patterns between 50, 100 and 200 m race distances has identified several variations. When compared to a typical 200 m stroke the 50 m stroke is characterised by a relative time increase to arm propulsion, arm recovery, leg propulsion and leg recovery phases (Chollet et al., 2004). Changes to the glide phase are also evident between race distances with decreases to the arm and leg glide phases common with decreasing race distance (Chollet et al., 2004; Nicol et al., 2021; Seifert & Chollet, 2005; Takagi et al., 2004). The increase to time spent in propulsive phases and decrease to time spent in glide phases with decreasing race distance reflects a need to overcome higher drag forces at greater velocities (Chollet et al., 2004). In addition to time spent in each phase, the total distance covered during the glide phase is reported to decrease as race distance decreases from 200 m to 50 m (0.50 m ± 0.25 – 0.22 m ± 0.20) (Leblanc et al., 2006). This pattern is also true when considered relative to total stroke distance (22.1% ± 8.3 – 11.1% ± 5.0) (Leblanc et al., 2006).

At present there is no consensus on temporal variations across race duration. In a study of 26 breaststroke specialists Oxford et al. (2017) identified no temporal changes to the propulsive or recovery phases over the duration of a 100 m time-trial (TT).

Conversely, temporal changes have been reported to occur over the duration of a 200 m TT (Louro et al., 2016). Temporal changes over a 200 m distance most commonly occur during the latter part of arm propulsion until the end of arm recovery and during the final 45°of leg extension (Louro et al., 2016). Other temporal phases remain relatively stable over race duration (Louro et al., 2016). Inconsistency in reported findings may reflect different temporal patterns between the 100 and 200 m event. This difference may otherwise be attributed to the use of different phase models between studies. Use of different models alters the calculation of time spent in each phase and makes comparison between studies difficult.

2.5.2.3 Between-Group Comparison Based on Experience Level

Between-group temporal comparisons based on performance level also frequented the literature. Typically categorised based on participants' personal best swimming times relative to the 50 m or 100 m breaststroke world record at the time of analysis, temporal comparisons between elite (within 80% of existing world record) and non-elite (outside 80% of existing world record) populations have been reported by several research groups .Temporal patterns were largely consistent between elite and non-elite groups with no differences in arm propulsion, arm glide or arm recovery identified (Leblanc et al., 2005). Similar findings were observed in lower limb temporal patterns. No differences in leg propulsion or leg recovery phases between elite and non-elite swimmers have been reported (Leblanc et al., 2005). Despite large similarities between elite and non-elite populations, temporal differences are reported during leg recovery one phase (time between the end of leg glide and the achievement of a 90° knee angle during recovery) in 200 m pace swimming for male swimmers of different experience levels (Leblanc et al., 2005). Elite males typically spend a longer amount of time in this phase when compared to non-elite males (14.2% ± 5.1 and 11.3% ± 3.4 respectively) (Leblanc et al., 2005). This finding may be attributed to a proportional decrease in the leg glide phase or greater range of knee flexion during leg recovery in elite swimmers (Leblanc et al., 2005). Temporal differences in female elite and non-elite populations occur during leg insweep and leg glide phases. Elite female swimmers spent longer in the leg insweep phase at 50 and 100 m paces (11.6% ± 2.1 and 9.3% ± 0.8 at 50 m pace and 11.6% ± 1.6 and 9.4% ± 0.8 at 100 m pace respectively) and less time in the leg glide phase at 100 and 200 m paces (46.5% ±

3.6 and 53.3% ± 5.7 at 100 m pace and 49.4% ± 4.6 and 56.0% ± 6.3 at 200 m pace respectively) (Leblanc et al., 2005).

Elite swimmers also typically travel further during each stroke phase when compared to non-elite swimmers (Komar, Sanders, et al., 2014; Leblanc et al., 2006). This is true for all temporal phases except for the glide phase at 90% of maximal speed (Komar, Sanders, et al., 2014). When normalised to total stroke distance (calculated as v/SR) however, non-elite swimmers travel further than elite swimmers during leg propulsion and glide phases (Leblanc et al., 2006). Elite swimmers continue to travel further during all other phases when considered in relative terms (Leblanc et al., 2006). The ability of elite swimmers to travel further during each temporal phase is attributed to their ability to maintain a streamlined position with one set of limbs during the propulsive phase of the other set of limbs. This finding may also result from higher acceleration values achieved by expert swimmers throughout propulsive phases (Komar, Sanders, et al., 2014).

Temporal comparisons between elite populations have also been reported. In the comparison of World Championship semi-finalists and preliminary swimmers semi-finalists typically spend longer in the arm glide phase than eliminated swimmers (Takagi et al., 2004). This pattern is consistent across all race distances and between male and female swimmers (Takagi et al., 2004). When compared to national medallist swimmers, World Championship athletes also spend less time in the leg recovery phase (0.46s ± 0.06 and 0.37s ± 0.09 respectively) (Olstad, Zinner, et al., 2017). Temporal differences observed between the highest performing athletes highlights the intricacy and complexity of temporal characteristics in elite breaststroke swimming. Further temporal investigation within elite populations is needed in order to develop a broader understanding of optimal temporal patterns.

2.5.2.4 Between-Group Comparison Based on Athlete Sex

The final characteristic that between-group temporal comparisons were made from was sex. Male swimmers typically spend longer in propulsive phases and less time in the arm glide phase when compared to female swimmers of the same experience level and swimming intensity (Nicol et al., 2021; Seifert & Chollet, 2005). These differences have been attributed to sex-based morphology variances. Due to their increased size and consequent large propelling surface male swimmers can generate greater mechanical outputs than female swimmers (Oxford et al., 2017). This may explain why male swimmers spend longer in propulsive phases. The reported difference in glide time between male and female swimmers may be attributed to an increased amount of adipose tissue typical to female morphology (Seifert & Chollet, 2005). This reduces the energy cost required to maintain a horizontal position required for an efficient glide phase (Seifert & Chollet, 2005).

2.5.2.5 Breaststroke Coordination Patterns

Temporal characteristics were also investigated through assessment of coordination. Coordination patterns were used to assess limb synchronicity between the discontinuous propulsive phases associated with breaststroke swimming. Two methods were commonly used to describe and evaluate coordination patterns in breaststroke swimming. The first method assessed coordination patterns through measurement of a number of time-gaps throughout the stroke cycle. Three time-gap models have been developed by various research groups (Table 2.10). The most commonly referenced time-gap model developed by Seifert and Chollet (2005) assessed coordination across five time-gaps (Seifert & Chollet, 2005; Seifert & Chollet, 2009; Seifert, Komar, Crettenand, Dadashi, et al., 2014). Using this method three modes of coordination were possible. Classification of each mode of coordination was dependant on the length of $T1_b$ (Chollet et al., 2004). When $T1_b > 0$ a glide mode of coordination occurs (Seifert, Komar, Crettenand, Dadashi, et al., 2014). This signifies that arm outsweep began after completion of the leg insweep phase. Opposition or continuous coordination occur when $T1_b = 0$ and superposition or overlap mode occur when $T1_b < 0$ (Chollet et al., 2004). This meant that the arm outsweep began at the same time, or prior to leg insweep completion (Chollet et al., 2004).

Coordination patterns are reported to differ between race distances. Between the 200 m and 50 m event the length of T1 decreases (Chollet et al., 2004). A similar pattern is not observed at time-gaps T2, T3 and T4. These coordination points do not vary between race distances (Chollet et al., 2004; Seifert & Chollet, 2005). The reduction in T1 indicates a shift towards a continuous or overlap mode of coordination as race distance decreases. A shift towards the continuous or overlap mode of coordination may be considered advantageous in the maintenance of a higher average velocity due to the reduction of IVV (Seifert & Chollet, 2005; Seifert, Komar, Crettenand, Dadashi, et al., 2014). These coordination modes are consequently considered most economical due to a reduction in mechanical energy output (Seifert, Komar, Crettenand, Dadashi, et al., 2014). Despite a reduction in mechanical energy output the use of continuous and overlap modes is often associated with an increase in SR and decrease in SL. The energetic cost of maintaining these modes of coordination over extended periods has not been investigated and warrants further research in order to better understand the influence of coordination mode selection on race performance.

Temporal phases and the time-gap method have been used in conjunction to assess the percentage of total stroke time spent in propulsion. Titled the index of flat breaststroke propulsion (IBFP), this parameter is calculated using a combination of leg propulsion time, arm propulsion time, elbow push time, $T1_a$, T2 and T3 (Equations 2.4-2.6) (Seifert & Chollet, 2005).

If $T1_a > 0$

$IBFP = leg\ propulsion + arm\ propulsion + elbow\ push - T1_a$ (2.4)

If $T1_a < 0$, $T2 < 0$ and $T3 < 0$

$IBFP = leg\ propulsion + arm\ propulsion + elbow\ push + |(T2 + T3)| - T1_a$ (2.5)

If $T1_a < 0$, $T2 > 0$ and $T3 > 0$

$IBFP = leg\ propulsion + arm\ propulsion + elbow\ push$ (2.6)

Note: all phase lengths used in IBFP calculations are derived from the stroke phase model described by Seifert and Chollet (2005). The IBFP is reported to increase with decreasing race distance in female swimmers but not male swimmers (Seifert & Chollet, 2005). Despite male swimmers maintaining a similar IBFP at all race distances, male swimmers continue to have a higher IBFP at all race distances when compared to female swimmers (Seifert & Chollet, 2005). This finding is consistent with stroke phase analysis that has consistently found male swimmers spend longer in both arm and leg propulsive phases than female swimmers (Seifert & Chollet, 2005).

The second method of coordination pattern assessment described coordination patterns through the analysis of elbow and knee angles (Komar, Sanders, et al., 2014). Titled the continuous relative phase (CRP) this method uses joint displacement and angular velocity to calculate a joint phase angle (Equation 2.7) (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014).

$\phi = \arctan\left(\frac{\omega_{norm}}{\theta_{norm}}\right)$ (2.7)

Where ω_{norm} refers to normalised values of angular velocity and θ_{norm} refers to normalised values of angular displacement. Elbow and knee phase angles are subsequently used to calculate the relative phase at a given time point (Equation 2.8) (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014).

$CRP = \phi_{elbow} - \phi_{knee}$ (2.8)

Using continuous relative phase two modes of coordination are possible: in-phase and anti-phase. In-phase coordination occurs when -30° < CRP < 30° and indicates that both sets of limbs are performing a similar motion (ie. both in flexion or both in extension) (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014). Anti-phase coordination occurs when -180° < CRP < -150° and 150° < CRP < 180° and indicates that each set of limbs is in opposing motion (ie. one set of limbs is flexing and one is extending) (Komar, Sanders, et al., 2014; Seifert, Komar, Crettenand, & Millet, 2014).

CRP patterns are reported to differ between individuals of various experience levels. Elite breaststroke swimmers typically exhibit lower relative phase values at maximal leg flexion when compared to recreational level swimmers (Komar, Sanders, et al., 2014). This results from elite swimmers reaching maximal elbow extension earlier than recreational swimmers at the same swimming intensity (Komar, Sanders, et al., 2014). Elite swimmers also exhibit lower maximal CRP values than recreational swimmers (Komar, Sanders, et al., 2014). This is attributed to elite swimmers achieving full elbow and knee extension during the glide phase. Recreational swimmers in comparison maintain small amounts of elbow and knee flexion throughout this phase and consequently maintain a higher CRP (Komar, Sanders, et al., 2014).

2.5.2.6 Association of Temporal Phases and Swimming Velocity

Using the above-described temporal models researchers have investigated the velocity patterns associated with various stroke phases. A typical time-velocity curve of the breaststroke stroke cycle is characterised by two maximums and two minimums (Figure 2.2). The time-velocity curve reaches its first minimum at maximal flexion of the lower limbs. This minimum is followed by an increase and maximum in velocity that occurs with extension of the lower limbs. As the lower limbs finish extension, the time-velocity curve again decreases before the upper limbs begin their propulsive phase. As the propulsive phase is initiated by the upper limbs the time-velocity curve again increases and reaches a second maximum towards the latter part of this phase, before decreasing during upper and lower limb recovery phases (Leblanc et al., 2006)

Velocity maxima associated with the pull and kick propulsive phases are of similar magnitude at submaximal intensity (Staniak et al., 2016). The velocity minima associated with the limb recovery and glide phases differ in magnitude at the same intensity. The velocity minimum associated with limb recovery is typically larger than that of the glide phase (Staniak et al., 2016).

Patterns within the breaststroke velocity trace are strongly associated with race performance. Higher minimum velocity throughout the stroke cycle (Takagi et al., 2004), a higher horizontal acceleration minimum during the glide phase ($r = -0.76$), smaller maximum vertical acceleration during the leg propulsion and glide phase ($r = 0.84$) and a reduced relative time to minimum vertical acceleration during leg propulsion and glide ($r = 0.91$) are strongly associated with faster 50 m time (Staniak et al., 2016). Swimmers should consequently aim to reduce deceleration throughout the glide phase and ensure force applied to the water during the leg propulsion phase is applied in the direction of travel in order to improve 50 m swimming time. Similar trends are yet to be established in 100 m and 200 m events and are of future research interest.

Table 2.9 Comparison of Stroke Phase Models Utilised Within the Breaststroke Biomechanics Literature.

Study	**Publication Year**	**Pull Phases**					**Kick Phases**				
Chollet et al.	2004	Arm glide	Arm propulsion	Elbow push	Recovery one	Recovery two	Leg propulsion	Leg insweep	Leg glide	Recovery one	Recovery two
Conceição et al.	2019		First propulsive action of arms	Second propulsive actions of arms			First propulsive action of legs	Second propulsive action of legs		Recovery	
Leblanc et al.	2005	Arm glide	Arm outsweep	Arm insweep	Recovery one	Recovery two	Leg propulsion	Leg insweep	Leg glide	Recovery one	Recovery two
Leblanc et al.	2007		Arm propulsion		Arm and leg recovery phase		Leg propulsion			Leg-arm lag phase	
Louro et al.	2016		First propulsive action of arms	Second propulsive actions of arms			First propulsive action of legs	Second propulsive action of legs		Recovery	
Nicol et al.	2021		Propulsive pull		Recovery pull		Propulsive kick			Recovery kick	
Oxford et al.	2017		Arm pull		Arm recovery		Leg kick			Leg recovery	

Seifert and Chollet	2005	Arm glide	Arm propulsion	Elbow push	Recovery one	Recovery two	Leg propulsion	Leg insweep	Leg glide	Recovery one	Recovery two
Seifert and Chollet	2009	Glide	Outsweep	Insweep	Recovery one	Recovery two	Propulsion	Insweep	Glide	Recovery one	Recovery two
Seifert et al.	2014	Glide	Outsweep	Insweep	Recovery one	Recovery two	Propulsion	Insweep	Glide	Recovery one	Recovery two
Staniak et al.	2016		Upper limb propulsion		Motion deceleration		Lower limb propulsion		Gliding		
Takagi et al.	2004	Glide	Outsweep	Insweep	Recovery		Sweep		Lift and glide	Recovery	

Table 2.10 Comparison of Time-Gap Models Described Within the Breaststroke Biomechanics Literature.

Time Period	Seifert & Chollet Model	Oxford et al. Model	Takagi et al. Model
Time between the end of leg propulsion and beginning of arm propulsion	$T1_a$	CP1	Simultaneous propulsion time
Time between the end of leg insweep and beginning of arm propulsion	$T1_b$	-	-
Time between the beginning of arm recovery and the beginning of leg recovery	T2	-	-
Time between the end of arm recovery and the end of leg recovery	T3	-	-
Time between 90° arm flexion during recovery and 90° leg flexion during recovery	T4	-	-
Time between the beginning of leg propulsion and the beginning of arm propulsion	-	Arm lag time	Percent arm lag time
Time between the end of arm propulsion and the beginning of leg propulsion	-	CP2	Simultaneous recovery time
Expression of coordination phases	% of total leg stroke time	% of total stroke time	% of total stroke time

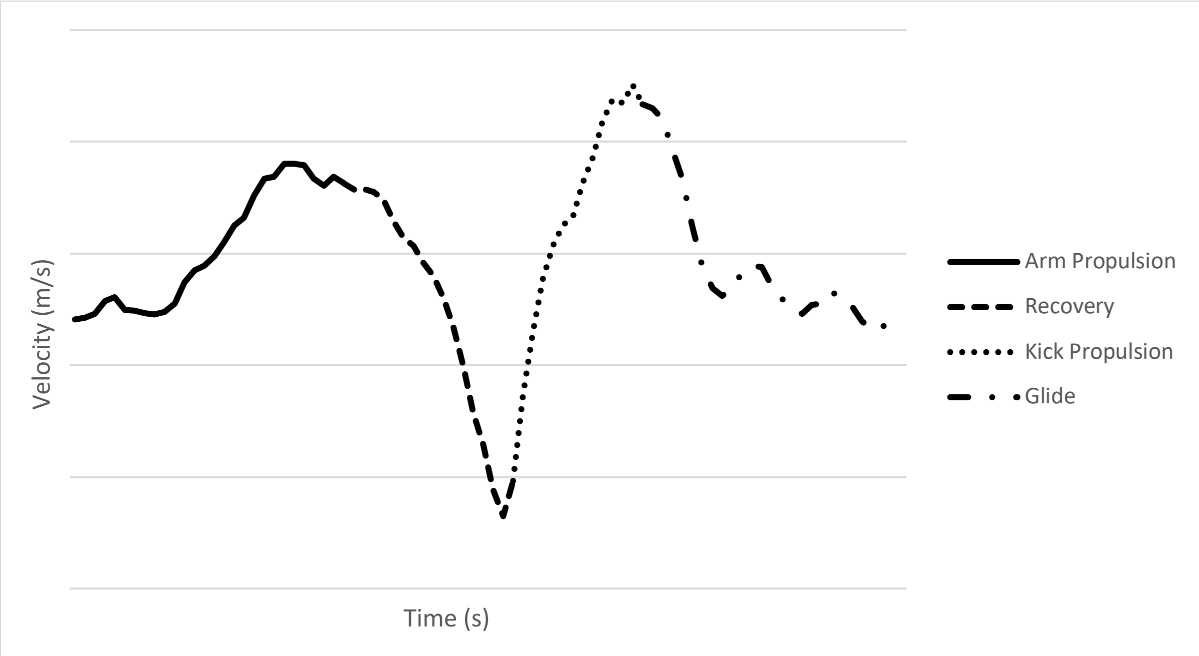

Figure 2.2 Time-Velocity Pattern of the Hip Across a Single Breaststroke Stroke Cycle.

2.5.3 Neuromuscular Activity

Neuromuscular activity of the triceps brachii (TB), biceps brachii (BB), trapezius (TRA), pectoralis major (PM), gastrocnemius (GAS), tibialis anterior (TA), bicep femoris (BF) and rectus femoris (RF) were most frequently reported in the literature due to their involvement in breaststroke swimming. Neuromuscular activity was discussed with reference to stroke phases, kinematics, intensity variations and experience-level based differences.

With reference to neuromuscular activation patterns across the stroke cycle, the TB, BB and PM are reported as most active during the arm propulsive phase (Olstad, Vaz, et al., 2017). Activation of the GAS, TA, RF, TRA and BF are conversely highest during the leg propulsion phase (Guignard et al., 2015; Olstad, Vaz, et al., 2017). The stroke cycle is initiated with activation of TB. TB activation at this time results in lateral hand movement characteristic of the beginning of arm propulsion (Olstad, Vaz, et al., 2017). Following lateral hand movement BB and PM are activated during the arm insweep phase in order to maximise arm propulsion (Olstad, Vaz, et al., 2017). The TRA is also activated during this time to assist in subsequent arm recovery (Olstad, Vaz, et al., 2017). Activation of TRA during arm recovery is coupled by activation of BF and GAS to initiate of leg recovery (Olstad, Vaz, et al., 2017). These muscles remain activated until maximal knee flexion is reached. RF remains inactive throughout this phase (Olstad, Vaz, et al., 2017). Once maximal knee flexion is achieved, the leg propulsion phase begins. The beginning of this phase is characterised by high levels of activation in the BF, RF and TA (Olstad, Vaz, et al., 2017). The TA at this time is responsible for controlling ankle dorsiflexion and the positioning of the feet to promote maximal propulsion (Olstad, Vaz, et al., 2017; Olstad, Zinner, et al., 2017). Propulsion generation during this phase is aided by activation of BF and RF to enable strong knee extension (Olstad, Vaz, et al., 2017). During the latter part of the leg propulsion phase GAS and TA activation increase in preparation for ankle plantarflexion required for an effective glide (Olstad, Vaz, et al., 2017). During this time TRA remains active in order to maintain a streamline position with the upper body (Olstad, Vaz, et al., 2017).

The patterning of neuromuscular activity across the stroke cycle is relatively similar at various swimming intensities (Olstad, Vaz, et al., 2017). The main point of difference between various intensity bouts is the timing of TB activation. At higher intensities TB activation occurs earlier within the stroke cycle (Olstad, Vaz, et al., 2017). Earlier TB activation signifies an earlier onset of the arm outsweep and a consequent reduction in glide time. This neuromuscular trend is consistent with an observed temporal shift towards continuous or overlapped modes of coordination with increasing intensity (Chollet et al., 2004). In addition to a time-shift in TB activation the magnitude of neuromuscular activation changes at various swimming intensities. Increases in intensity are coupled with an increase to the sum of total integrated EMG (iEMG) (Olstad, Vaz, et al., 2017). This trend is consistent across TB, BB, PM, GAS, TA, BF and RF (Olstad, Vaz, et al., 2017). In addition to neuromuscular activity differences associated with varying intensity, neuromuscular activity is also reported to vary with changes to SR (Conceição et al., 2013). These changes are observable in the frequency of TB, BB and PM, with frequency reductions associated with an increase in breaststroke SR (Conceição et al., 2013).

Several differences in neuromuscular activity patterns have been reported between beginner and elite groups. Despite some pattern similarities activation time-shifts to the PM, BB, RF and TA are common (Vaz et al., 2016). Elite swimmers typically activate TA later in the leg recovery phase when compared to beginner-level swimmers (Vaz et al., 2016). The later activation of TA during this phase delays the initiation of ankle dorsiflexion and consequently minimises drag towards the latter part of this phase (Vaz et al., 2016).

Neuromuscular activity differences have also been reported within elite populations. When compared to national-elite breaststroke swimmers, international medallists typically activate BB and PM earlier in the arm propulsive phase (Olstad, Zinner, et al., 2017). Earlier BB and PM activation signifies an earlier onset of the arm insweep and a consequent ability to generate greater propulsion (Olstad, Zinner, et al., 2017). Neuromuscular differences between these two performance-level groups are also common during the leg recovery phase. International medallists typically activate BF for a longer period during this phase when compared to national-elite swimmers (Olstad, Zinner, et al., 2017). Longer activation indicates maintenance of more neuromuscular activity during the leg recovery phase and may explain an observed reduction in leg recovery time when compared to national-elite swimmers (Olstad, Zinner, et al., 2017). International medallists also typically activate TA later in this phase (Olstad, Zinner, et al., 2017). Similar to conclusions drawn from comparison of beginner and elite populations the latter activation of TA at this time reduces resistive forces experienced by international medallists at maximal knee flexion (Olstad, Zinner, et al., 2017). Another characteristic common to international medallists is the activation of GAS during the leg glide phase (Guignard et al., 2015; Olstad, Zinner, et al., 2017). This suggests the use of ankle plantarflexion to reduce drag throughout the glide phase and is a characteristic not frequently seen amongst national-elite athletes (Olstad, Zinner, et al., 2017). The final point of difference between national-elite and international medallists is an increased level of TB activation during the beginning of the leg propulsion phase (Olstad, Zinner, et al., 2017). The higher level of TB activation observed in national-elite swimmers may indicate the onset of leg propulsion prior to the end of arm extension (Olstad, Zinner, et al., 2017). This observation may otherwise be indicative of the use of TB to maintain upper body streamline during the leg propulsion phase (Olstad, Zinner, et al., 2017). Performance-level based comparisons in neuromuscular activity highlight a number of variances that increase propulsion, reduce resistive forces and may delay muscle fatigue onset in international medallists.

Consideration of these factors should be made in the adaptation of breaststroke technique to maximise performance.

Despite emerging evidence to support neuromuscular differences between national-elite and international medallist breaststroke swimmers, the limited size of samples hinders the generalisability of reported findings to the broader elite population. Described neuromuscular differences may be partially attributed to use of individualistic neuromuscular patterns to produce the same movement (Conceição et al., 2019; Guignard et al., 2015). It is also possible that some athletes use muscles that are not frequently investigated within the literature during breaststroke swimming. Further investigation into neuromuscular activity patterns within and between elite populations is required to validate preliminary findings.

2.5.4 Pacing

Few research articles have investigated breaststroke pacing profiles. Despite a small amount of research, the existing literature is in consensus regarding pacing characteristics in elite breaststroke swimming.

Elite breaststroke events consistently model a positive pacing profile. This profile is characterised by a reduction is swimming speed over each consecutive 50 m split (Skorski et al., 2014; Thompson et al., 2000). Positive pacing profiles in breaststroke swimming are commonly used across 100 and 200 m race distances, by male and female swimmers (Gonjo & Olstad, 2021; Thompson et al., 2000; Thompson et al., 2003; Thompson, Haljand, et al., 2004) and during both heat and final races (Skorski et al., 2014). The positive profile characteristic to breaststroke racing is unique within competitive swimming due to the comparatively large split time variability (Skorski et al., 2014). The reduction in speed over the duration of a race is consequently more than typical for any other event.

Despite common use of a positive pacing strategy in breaststroke swimming, debate exists regarding its effect on performance. When compared to an even pacing strategy (similar speed over consecutive 50 m splits) a positive pacing strategy is associated with high post-effort blood La^+ and higher rate of perceived exertion (Thompson et al., 2003). These differences are attributed to a greater intensity during early stages of the effort and a consequent increase in lactate accumulation time (Thompson et al., 2003). A positive pacing strategy is also associated with higher SR over the first half of a 175 m effort when compared to an even pacing strategy (Thompson et al., 2003). SR differences are not apparent over the final half of a 175 m effort (Thompson et al., 2003). Given the increase in energy cost associated with increasing SR (Barbosa, Fernandes, Keskinen, et al., 2008) it may be suggested that the use of a positive pacing strategy increases total energy cost over an event. In response to these findings it has been suggested that the use of an even pacing strategy may delay the onset of fatigue (Thompson et al., 2003). The adoption of an even pacing strategy may consequently aid in the maintenance of a higher average velocity throughout an event. This hypothesis is yet to be empirically tested however warrants further investigation. Also of future research interest is how the use of various pacing strategies influence biomechanical parameters including temporal patterns and propulsion characteristics.

Support for further investigation into the role of pacing profiles on overall race performance is warranted based on correlational analysis that has reported the relationship between split times and overall race time. Of all splits available, final lap time is most strongly correlated to overall time in male 100 m finalists (r = 0.80), female 100 m finalists (r = 0.83) and male 200 m finalists (r = 0.67) at international competition. Lap three is most strongly associated with 200 m race time in female swimmers at international competition (r = 0.91) (Robertson et al., 2009). Given the strong association between final lap time and overall race time it may be expected that swimmers who are able to maintain or reserve their speed for the final lap may have a faster overall race time than swimmers who use their speed over the first lap. This racing strategy closely reflects that of an even or negative pacing strategy and may suggest the positive pacing profile most commonly adopted in breaststroke racing is not the most advantageous for minimising overall race time.

2.5.5 Kinetics

An emerging area of interest in breaststroke biomechanics is kinetics. Only two of the 35 research studies included in this review considered force production in investigation of breaststroke swimming. Existing research into swimming force outputs has found breaststroke swimmers produce the highest absolute and relative (normalised to body mass) maximum tethered swimming forces of all four competitive stroke specialists

(Morouço, Keskinen, et al., 2011). This finding was attributed to the simultaneous propulsive movements of each pair of limbs and the powerful leg kick unique to breaststroke swimming (Morouço, Keskinen, et al., 2011)

Force profile characteristics have been associated with swimming and breaststroke kicking performance. Absolute maximum and average force production during a tethered 30 s maximum effort have been significantly associated with breaststroke swimming velocity at 50, 100 and 200 m distances ($r = 0.90$, 0.77 and 0.66 for maximum values respectively and $r = 0.94$, 0.86 and 0.80 for mean values respectively) (Morouço, Keskinen, et al., 2011). Average force production is more closely correlated to swimming velocity than maximum force production at all distances (Morouço, Keskinen, et al., 2011). The strength of the relationship between force production and velocity decreases as race distance increases (Morouço, Keskinen, et al., 2011).

A force-velocity relationship has also been established between fluid forces acting upon the foot and breaststroke kicking performance. In an investigation of eight national-level breaststroke swimmers Tsunokawa et al. (2015) identified a strong correlation between fluid force impulse and average velocity over a 50 m breaststroke kick time-trial ($r = 0.87$). The relationship between force output and average velocity over a 50 m breaststroke kick time-trial however, was not significant when maximal force output was considered ($p > .05$).

Kinetics in breaststroke swimming is a relatively under-researched area of study. The strength of associations reported by Morouço, Keskinen, et al. (2011) and Tsunokawa et al. (2015) should promote interest in the practical application of force testing in the elite swimming environment.

2.6 Conclusion

Empirical investigation of elite breaststroke biomechanics over the past two decades has largely centred on kinematics, temporal analysis and neuromuscular activity. Research in these areas has typically reported between-group differences between athletes of various experience or performance level, race distance and sex.

Irrespective of their prevalence within the literature several research groups have suggested these parameters be better investigated on an individual basis to best understand kinematics, temporal patterns and neuromuscular activity within an elite population. Research with an individualistic approach remains relatively uncommon within the relevant literature, with Sanders, Fairweather, et al. (2015) the only reviewed article to adopt a case study approach to analysis.

Despite existing shortcomings, research to date has provided coaches and performance scientists with a breadth of knowledge to influence technical prescription and optimise breaststroke swimming performance at an elite level. Based on the existing literature, coaches and performance scientists should consider the identification of an optimal SR to SL ratio on an individual basis and monitor kinematic changes across race duration. Coaches and performance scientists may also consider the temporal characteristics typical of an athlete's primary event to ensure their athlete coordinates limb movements efficiently. With consideration of the above factors and individual athlete characteristics, coaches and performance scientists will be well positioned to make meaningful changes to breaststroke athlete performance at an elite level.

Chapter Three: The Temporal Analysis of Elite Breaststroke Swimming During Competition

This chapter includes a published, co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:

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My contribution to the paper involved study conception and design, data collection, data analysis and interpretation, and manuscript preparation.

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The Temporal Analysis of Elite Breaststroke Swimming During Competition

3.1 Abstract

Breaststroke is the only competitive stroke characterised by two, discontinuous propulsive phases. It is consequently paramount that swimmers optimally coordinate limb movements in order to maintain the highest average velocity possible. The present study aimed to investigate the temporal patterns of elite breaststroke swimmers. 50 m long-course competition footage of (1) 20 male 100 m races, (2) 24 female 100 m races, (3) 15 male 200 m races, and (4) 27 female 200 m races from 2018 to 2020 were digitised and analysed. Six points within each stroke cycle were identified and used to calculate 15 temporal parameters. Analyses revealed multiple temporal pattern differences between groups based on sex and race distance. It is recommended that coaches individualise swimmers' breaststroke temporal patterns based on individual needs, strengths, and morphological characteristics.

3.2 Introduction

The propulsive pattern of breaststroke swimming is unique amongst the competitive strokes. Dissimilar to butterfly, backstroke and freestyle, the propulsive pattern in breaststroke is characterised by two, discontinuous propulsive phases. These phases occur sequentially beginning with upper limb propulsion and followed by lower limb propulsion. The sequential patterning of the upper and lower limbs result in a multitude of possible temporal patterns.

Temporal patterns are described in relation to stroke phases. The stroke cycle in breaststroke swimming is broadly divided into two phases: pull and kick. Each phase is further separated into three sub-phases: propulsion, recovery and glide (Takagi et al., 2004). Within each sub-phase a number of movements occur; these movements have been described in a number of ways. One of the most widely used phase models developed by Chollet et al. (2004) describes each of the pull and kick phases in five sub- phases (Table 3.1). The time spent within each sub-phase is used to determine temporal characteristics of the stroke.

The unique temporal patterns associated with breaststroke swimming result in a velocity profile dissimilar to the remaining competitive strokes. The time-velocity profile of breaststroke swimming is associated with two maximums and two minimums (Figure 2.2) (Leblanc et al., 2006). The first acceleration phase and velocity maximum are associated with the arm propulsive phase (Leblanc et al., 2006). This peak is followed by a deceleration phase and velocity minimum that occurs during the arm and leg recovery phases (Leblanc et al., 2006). As the leg propulsion phase is initiated, velocity again increases and reaches its second maximum (Leblanc et al., 2006). This maximum is followed by a second deceleration phase and minimum that is associated with leg in-sweep and glide phases (Leblanc et al., 2006).

Temporal patterns can also be used to describe coordination throughout the breast-stroke cycle. Coordination patterns are described with reference to the time spent between various sub-phases. Four time-gaps are calculated within the breaststroke cycle (Table 3.2). Using these time gaps, breaststroke coordination may be categorised into one of three modes: glide, continuous and overlapped (Leblanc et al., 2009; Maglischo, 2003; Seifert & Chollet, 2005; Takagi et al., 2004). Each mode differs in the length of the time gap between the end of the leg in-sweep phase and the beginning of the following arm propulsion ($T1_b$) (Leblanc et al., 2009; Maglischo, 2003; Seifert & Chollet, 2005; Takagi et al., 2004). Glide coordination has the greatest time gap ($T1_b > 0$), followed by continuous coordination ($T1_b = 0$) (Seifert & Chollet, 2005). Overlapped coordination has no time gap and is characterised by the arm propulsion phase beginning before completion of the leg in-sweep phase ($T1_b < 0$) (Seifert & Chollet, 2005).

Temporal pattern variations commonly occur between race distances. The stroke utilised during a 50 m event is characterised by an increase in arm propulsion (30.7 ± 6.1% to 34.4 ± 6.1 % for males and 21.7 ± 2.9% to 26.0 ± 2.9% for females), decrease in arm glide (43.6 ± 7.9% to 37.8 ± 8.4% for males and 55.1 ± 5.0% to 44.9 ± 5.5% for females) and increase in the leg propulsive phase (15.5 ± 3.9% to 18.3 ± 3.8% for males and 12.8 ± 2.2% to 16.2 ± 3.6% for females) when compared to the 200 m event (Leblanc et al., 2005). Coordination changes associated with race distance most frequently occur at $T1_b$ (Leblanc et al., 2005). The reduction in $T1_b$ during a 50 m event

(−25.8 ± 7.6% to −10.4 ± 7.8% of complete leg stroke) indicates the shortening of body glide and a move towards continuous and overlapped modes of coordination (Chollet et al., 2004). Due to the limited amount of research that has investigated temporal characteristics amongst an elite population, it is unclear whether these trends are generalisable to all elite breaststroke swimmers.

Stroke analysis also indicates a difference in temporal patterns between males and females at the same race distance. During a 200 m event, males typically spend longer in the arm propulsive phase (30.7 ± 6.1 compared to 21.7 ± 2.9%), the leg propulsive phase (15.5 ± 3.9% compared to 12.8 ± 2.2%) and have a shorter body glide (−18.2 ± 7.6% compared to −24.9 ± 4.7%) when compared to female swimmers (Leblanc et al., 2005). This pattern is consistent across 100 m and 50 m events. Temporal pattern differences between males and females have been attributed to an increased amount of propulsion produced by male swimmers (Seifert & Chollet, 2005) and an increased level of floatation held by female swimmers (Leblanc et al., 2010). This increase in floatation enables female swimmers to maintain velocity during the glide phase and may explain the difference in body glide duration between sexes.

Research investigating temporal characteristics has significantly contributed to the understanding of breaststroke swimming in constrained environments. However, little remains known about temporal characteristics in competition. Much of the relevant literature to date has used 25 m efforts at simulated race paces to assess temporal characteristics (Chollet et al., 2004; Leblanc et al., 2005; Leblanc et al., 2009; Seifert & Chollet, 2005). This method assumes that temporal patterns used during simulated race speed reflect those during competition. The analysis of temporal characteristics during competition would also enable the investigation of temporal changes that occur over the course of an event.

The present study addressed this limitation within the literature through the investigation of temporal characteristics in elite competition. The first aim of the present study was to characterise and present normative values of the temporal properties of elite breaststroke swimmers during competition in the 100 m and 200 m events. The second aim was to determine the temporal differences between male and female breaststroke swimmers, and between 100 m and 200 m events. The final aim of this study was to determine the temporal parameters with greatest importance to overall race time in the male 100 m, male 200 m, female 100 m and female 200 m events. Based on the existing literature it was hypothesised that temporal pattern differences would be evident between groups based on sex and race distance. It was also hypothesised that the temporal parameters of most importance to overall swimming performance would be similar between male and female athletes, and between 100 m and 200 m race distances. Findings of this investigation will inform future breaststroke training interventions and competition strategies.

Table 3.1 Chollet et al. (2004) Breaststroke Phase Model.

Phase	Time Period
Arm glide	Extension of the arms until the beginning of the backwards hand movement.
Arm propulsion	Beginning of the backwards hand movement until the end of the backwards hand movement.
Elbow push	End of the backwards hand movement until the beginning of the forward hand movement.
Recovery one (arms)	End of the elbow push until the arm/forearm angle reaching 90°.
Recovery two (arms)	Arm/forearm angle reaching 90° until the extension of the arms.
Leg propulsion	Beginning of the backward movement of the feet until leg extension.
Leg in-sweep	End of leg extension until joining of legs.
Leg glide	Leg joining until beginning the forward movement of the feet.
Recovery one (legs)	Beginning of the feet forward movement until the thigh/leg angle reaching 90°.
Recovery two (legs)	Thigh/leg angle reaching 90° until the end of the feet forward movement.

Table 3.2 Time Gaps in the Stroke Cycle of Breaststroke.

Time Gap	Time period
$T1_a$	End of leg propulsion and beginning of arm propulsion.
$T1_b$	End of leg in-sweep and beginning of arm propulsion.
T2	Beginning of arm recovery and beginning of leg recovery.
T3	End of arm recovery and end of leg recovery.
T4	Arm flexion during the recovery phase reaching 90° and leg flexion during the recovery phase reaching 90°.

Note. Adapted from Chollet et al. (2004).

3.3 Methods

3.3.1 Participants

Race data from 86 elite breaststroke race performances were analysed in this study. All swimmers specialised in breaststroke as their preferred stroke and had at least five years of competitive experience at a national level. The data set included multiple World Record holders, Olympic medallists and World Champions over the 100 m and 200 m events. Further details about the sample are provided in Table 3.3. Approval for the use of race footage from national athletes was provided by the Griffith University Ethics Committee (2019/359). All race footage from international athletes was broadcast on various streaming services during competition and was consequently in the public domain.

Table 3.3 Sample Characteristics.

Subgroup	Number of Athletes	Athlete Age	Total Race Time (s)	FINA Points
Male 100	20	22.20 ± 3.37	60.19 ± 1.75	857.60 ± 73.38
Male 200	15	21.12 ± 3.11	131.17 ± 4.42	904.93 ± 89.16
Female 100	24	21.50 ± 3.46	68.63 ± 2.63	822.58 ± 89.73
Female 200	27	21.15 ± 3.38	147.36 ± 5.04	847.15 ± 83.38

3.3.2 Data Collection

Data was collected across multiple 50 m long-course meets throughout 2018, 2019 and 2020. A singular panning-camera (Canon Camcorder XF200, Canon, Australia) was mounted on a tripod (Benro Aero4) at the top of the side grandstand and recorded each race at 50 Hz in 1080p. The position of the camera was as close to 25 m along the length of the pool and approximately 10–20 m above water level. Given that no positional parameters were analysed in this study, standardised positioning of the camera was not essential. Camera zoom was standardised to a field of view that included three lanes: the swimmer’s lane, one lane above and one lane below.

Heat, semi-final and final breaststroke races filmed by the Australian National Performance Analysis Team throughout the domestic and international racing season were considered for inclusion. Only long-course (50 m) races were included. Races were excluded if the swimmer was not in the centre of the frame for the entirety of the race, if one or more frames were dropped during recording, if vision was obstructed by persons or water turbulence, or if the clip did not include the start/finish. Once the available dataset was finalised, a single 100 m and 200 m race for each athlete was selected for analysis based on fastest total race time. A total of 86 race performances were included in analysis. The final dataset consisted of 20 male 100 m races, 24 female 100 m races, 15 male 200 m races and 27 female 200 m races.

3.3.3 Temporal Analysis

The investigation of temporal characteristics was conducted through the analysis of stroke phases. Video footage of each race was analysed using a proprietary swimming race analysis software called SPARTA (Canberra, Australia). This software enabled frame-by-frame playback of recorded footage and was used to identify the frame number of six time points within each stroke cycle (Table 3.4). The frame number of each time point was subsequently entered into a custom Shiny Application (R Studio Version 1.4.0, R Studio Inc, Boston, USA). This application calculated 15 stroke parameters from each stroke cycle (Table 3.5). Absolute parameter calculations were subsequently converted to percentage-based values according to Table 3.5. Percentage-based values were used throughout analysis to ensure sub-group comparisons were not biased by stroke rate. Parameters were saved into a comma-separated values file (CSV) for statistical analysis.

Mid-pool strokes were selected to avoid temporal changes that result from the start, turn or finish. Six strokes (stroke number 6–11) were analysed each lap. These strokes were selected after a preliminary analysis found that the timing characteristics of strokes 6–20 were similar on any given lap (SD = 0.03 seconds across all temporal parameters). The selection of the same six strokes ensured consistency across all races.

Method reliability was assessed using a two-way mixed effect, consistency, multiple raters interclass correlation coefficient (ICC). One male and one female race were selected at random and analysed 10 times by each analyst over a number of different sessions. ICC = 1.00 for all parameters. Method reliability was further assessed through manual calculation of the number of frames that differed between inter- and intra-raters at each digitised stroke point. Differences of up to two frames were observed at each digitised stroke point, which equated to 0.04 of a second. This time difference was considered within acceptable limits and the analysis method was consequently deemed reliable. All male races were processed by a single analyst and all female races were processed independently by another analyst to further limit inter-tester variability and preserve the integrity of the analysis process.

Table 3.4 Digitised Stroke Points.

Stroke Point	Description
Start Pull	First frame of forceful lateral hand movement.
Finish Pull	Last frame before the hands move forward.
Finish Drive	Frame when face first hits water with full elbow extension.
Start Recovery Kick	First frame of knees flexion.
Start Propulsive Kick	First frame of backward feet movement.
Finish Propulsive Kick	First frame when the feet come together.

Table 3.5 Breaststroke Parameter Table.

Parameter	Definition	Calculation	Percentage Calculation
Propulsive Delay (s).	Time between the end of propulsive pull and the beginning of propulsive kick.	Start propulsive kick – finish pull.	Total stroke time.
Drag Time (s).	Time between the end of arm extension and the beginning of propulsive kick.	Start propulsive kick – finish drive.	Total stroke time.
Stroke Rate (stroke/m).	Number of strokes taken per minute.	60/(finish pull two – finish pull one).	NA
Total Stroke Time (s).	Time between first lateral hand movement of consecutive strokes.	Start pull two – start pull one.	NA
Total Pull (s).	Time between the first lateral hand movement and the end of elbow extension.	Finish drive – start pull.	Total stroke time.
Propulsive Pull (s).	Time between the first lateral hand movement and the beginning of forward hand movement.	Finish pull – start pull.	Total pull time.
Recovery Pull (s).	Time between the first forward movement of the hands and the face hitting the water with elbows fully extended.	Finish drive – finish pull.	Total pull time.
Pull Delay (s).	Time between the end of elbow extension and the beginning of the next lateral hand movement.	Start pull two – finish drive one.	Total stroke time.
Total Kick (s).	Time between the initiation of knee flexion and the feet coming together.	Finish propulsive kick – start kick recovery.	Total stroke time.
Recovery Kick (s).	Time between the initiation of knee flexion and the feet beginning to move backward.	Start propulsive kick – start kick recovery.	Total kick time.
Propulsive Kick (s).	Time between the first backward movement of the feet and the feet coming together.	Finish propulsive kick – start propulsive kick.	Total kick time.
Passive Kick (s).	Time between the feet coming together and the initiation of knee flexion.	Start recovery kick two – finish propulsive kick one.	Total stroke time.

Kick Delay (s).	Time between the first lateral hand movement and the initiation of knee flexion.	Start kick recovery – start pull.	Total stroke time.
Glide (s).	Time between the feet coming together and the first lateral movement of the hands.	Start pull – finish propulsive kick.	Total stroke time.
Total Movement Time (s).	Time between the first lateral hand movement and the feet coming together.	Finish propulsive kick – start pull.	Total stroke time.

3.3.4 Statistical Analysis

Prior to analysis, the dataset was screened for outliers through visual inspection of scatterplots. All subsequent analysis was conducted using RStudio (Version 1.3.1056, R Studio Inc, Boston, USA).

The dataset was initially filtered into sub-groups based on race distance and sex (Male 100 m, Male 200 m, Female 100 m, Female 200 m). A series of descriptive statistics were subsequently calculated for temporal parameters within each sub-group. Following descriptive analysis, a series of unpaired two-tailed t-tests were run in order to determine the statistical significance of observed temporal differences between race distances and sexes. Shapiro-Wilk and F-tests were used to assess parameter normality and variance. In the event that the assumption of normality or equal variance was violated ($p < .05$), an unpaired two-tailed Wilcoxon test was used to assess the statistical significance of observed temporal differences between each sub-group.

The importance of temporal parameters to total race time was evaluated using multiple linear regression; these statistical methods were similar to those employed by Nicol et al. (2019) and Tor et al. (2015) Four parameters were selected for inclusion in regression analysis: propulsive pull time, propulsive delay, propulsive kick time and glide time. Parameters were selected based on their correspondence to an acceleration or deceleration phase in a typical time–velocity curve (Leblanc et al., 2006). Selected parameters were then entered into a stepwise regression and the most parsimonious model selected to represent the relationship between temporal parameters and overall race time. The association between parameters included in each model and total race time were evaluated using Pearson's correlations.

Correlation coefficient values of $r \leq 0.30$, $0.30 < r < 0.70$ and $r \geq 0.70$ were interpreted as weak, moderate, and strong associations respectively.

3.4 Results

3.4.1 Descriptive Analysis

Analysis of breaststroke swimming revealed significant differences in temporal characteristics based on sex and race distance. Table 3.6 details the descriptive results for each sub-group and the significance of observed differences. For both male and female athletes, the 100 m stroke was characterised by reductions to the percentage of stroke time spent in pull delay, recovery kick, passive kick and glide when compared to the 200 m stroke. The 100 m stroke was also characterised by a larger percentage of stroke time spent in total kick, propulsive kick, kick delay and total movement time. Significant differences were also observed in propulsive pull time and recovery pull time between the male 100 m and 200 m events. Male athletes spent a greater percentage of total pull time in the propulsive pull phase and a lower percentage of time in the recovery pull phase during the 100 m event. A similar trend in pull characteristics was observed in female athletes, however, was not statistically significant.

Temporal differences between male and female athletes were also evident. The comparison of male and female 100 m stroke characteristics revealed significant differences in all temporal parameters with the exception of total kick time, propulsive kick time and passive kick time. At this distance, males typically spent a smaller percentage of time in propulsive delay, drag, recovery pull, pull delay, recovery kick and glide when compared to females. Male athletes also typically spent a greater percentage of time in total pull, propulsive pull, propulsive kick, kick delay and total movement time.

Comparison of 200 m stroke characteristics between male and female athletes revealed significant temporal differences in all calculated parameters. Male athletes typically spent a smaller percentage of time in the propulsive delay, drag, recovery pull, pull delay, total kick, recovery kick and glide phases when compared to female athletes. Males also spent a longer percentage of stroke time in the total pull, propulsive pull, propulsive kick, passive kick, kick delay and total movement time phases than females at this race distance.

Table 3.6 Breaststroke Temporal Pattern Descriptive Analysis.

Parameter	*Female 100*		*Female 200*		*Male 100*		*Male 200*	
	% Based Mean and Standard Deviation	% Based Range	% Based Mean and Standard Deviation	% Based Range	% Based Mean and Standard Deviation	% Based Range	% Based Mean and Standard Deviation	% Based Range
Propulsive Delay	24.35 ± 3.34 [c]	18.36 – 33.85	23.41 ± 3.16 [d]	15.93 – 30.97	20.55 ± 3.70	14.17 – 28.25	20.51 ± 2.98	14.78 – 27.58
Drag Time	4.69 ± 3.26 [a,c]	0.00 – 13.24	6.01 ± 3.02 [d]	0.00 – 15.77	1.08 ± 1.78	0.00 – 6.60	1.64 ± 2.00	0.00 – 6.89
Total Pull Time	65.64 ± 8.52 [a,c]	49.71 – 89.26	56.10 ± 7.69 [d]	39.81 – 76.05	74.92 ± 6.95 [b]	64.52 – 97.68	64.97 ± 8.98	49.56 – 89.82
Propulsive Pull Time	69.64 ± 3.36 [c]	63.17 – 78.12	69.00 ± 3.89 [d]	61.10 – 90.51	72.48 ± 4.98 [b]	60.63 – 80.75	69.42 ± 5.68	51.77 – 77.18
Recovery Pull Time	30.36 ± 3.36 [c]	21.88 – 36.83	31.00 ± 3.89 [d]	9.49 – 38.90	27.52 ± 4.98 [b]	19.25 – 39.37	30.58 ± 5.68	22.82 – 48.23
Pull Delay	34.41 ± 8.73 [a,c]	10.75 – 51.63	43.96 ± 7.84 [d]	23.13 – 64.39	25.14 ± 7.12 [b]	0.43 – 35.75	34.97 ± 9.02	9.58 – 51.06
Total Kick Time	51.92 ± 6.23 [a]	40.17 – 66.83	45.65 ± 4.85 [d]	36.18 – 62.20	51.27 ± 5.91 [b]	40.78 – 63.91	43.61 ± 4.58	34.82 – 53.70
Recovery Kick Time	41.50 ± 4.34 [a,c]	30.86 – 49.13	44.03 ± 3.77 [d]	35.03 – 51.77	34.19 ± 3.90 [b]	25.92 – 42.68	38.05 ± 3.58	31.33 – 46.37
Propulsive Kick Time	58.50 ± 4.34 [a,c]	50.87 – 69.14	55.97 ± 3.77 [d]	48.23 – 64.97	65.81 ± 3.90 [b]	57.32 – 74.08	61.95 ± 3.58	53.63 – 68.67
Passive Kick Time	48.00 ± 6.06 [a]	30.98 – 60.12	54.28 ± 4.90 [d]	38.19 – 64.30	49.03 ± 5.71 [b]	38.98 – 59.98	56.48 ± 4.64	46.04 – 65.04
Kick Delay	48.46 ± 6.38 [a,c]	32.85 – 60.00	41.85 ± 6.48 [d]	29.29 – 58.62	56.75 ± 5.30 [b]	47.13 – 69.10	48.94 ± 7.92	33.03 – 70.86
Glide Time	0.04 ± 0.05 [a,c]	0.00 – 0.19	0.13 ± 0.07 [d]	0.00 – 0.29	0.01 ± 0.02 [b]	0.00 – 0.05	0.09 ± 0.07	0.00 ± 0.24
Total Movement Time	95.84 ± 4.97 [a,c]	81.24 – 100.00	87.11 ± 7.18 [d]	70.63 – 100.00	98.99 ± 1.65 [b]	94.36 – 100.00	90.65 ± 6.83	76.46 – 100.00

[a] $p < .05$ between Female 100 and 200

[b] $p < .05$ between Male 100 and 200

[c] $p < .05$ between Female and Male 100

[d] $p < .05$ between Female and Male 200

3.4.2 Regression Analysis

Regression analysis produced a different model for each sub-group. Tables 3.7 – 3.10 detail the regression output for each subset. Analysis of the female 100 m event found the percentage of total pull time spent in the propulsive phase to be the sole best predictor of overall race time. This parameter accounted for 37.4% of variance. Percentage of propulsive pull time was moderately correlated to overall race time ($r = 0.36$).

Percentage of total pull time spent in the propulsive phase, percentage of total kick time spent in the propulsive phase and glide time were included in the final model for the male 100 m event. Together these parameters accounted for 49.8% of total variance in overall race time. Propulsive pull time was moderately correlated to overall race time ($r = -0.38$). Propulsive kick time and glide time were weakly correlated to overall race time ($r = -0.27$ and -0.10 respectively), however, these relationships were not significant.

Analysis of the female 200 m event identified the percentage of total pull time spent in the propulsive phase and propulsive delay as the best predictors of overall race time. Both predictors were weakly correlated to overall race time ($r = 0.15$ and 0.13 respectively) and these relationships did not reach statistical significance.

Two parameters were included in the final regression model for the male 200 m event. Together, the percentage of total pull time spent in the propulsive phase and the percentage of total stroke time spent in the glide phase accounted for 27.0% of total variance. Both parameters were weakly correlated to overall race time ($r = -0.29$ and -0.18 respectively), however, the relationship between percentage of total stroke time spent in glide and overall race time was not statistically significant.

Table 3.7 Female 100 m Regression Results.

Female 100					
Parameter	**B**	**r**	**p**	**Full Model**	
Constant	48.97			R^2	0.37
Propulsive pull time	0.28	0.36	0.01*	MAE	2.40

Table 3.8 Female 200 m Regression Results.

Female 200					
Parameter	**B**	**r**	**p**	**Full Model**	
Constant	119.79			R^2	0.10
Propulsive pull time	0.29	0.15	0.12	MAE	4.96
Propulsive delay	0.33	0.13	0.18		

Table 3.9 Male 100 m Regression Results.

Male 100					
Parameter	**B**	**r**	**p**	**Full Model**	
Constant	75.28			R^2	0.50
Propulsive pull time	-0.12	-0.38	0.02*	MAE	1.65
Propulsive kick time	-0.09	-0.27	0.09		
Glide time	-15.03	-0.10	0.53		

Table 3.10 Male 200 m Regression Results.

Male 200					
Parameter	**B**	**r**	**p**	**Full Model**	
Constant	151.79			R^2	.27
Propulsive pull time	-0.27	-0.29	0.03*	MAE	3.87
Glide time	-17.32	-0.18	0.16		

3.5 Discussion & Implications

The present study was one of the first to investigate the temporal patterns of elite breaststroke swimming in competition. Eighty-six elite international races were analysed to evaluate temporal pattern differences between 100 m and 200 m race distances and between male and female athletes. Statistical analyses revealed temporal differences between sub-groups, based on sex and race distance. This finding supported the first hypothesis. Analyses also found different temporal parameters to account for variance in overall race time between male, female, 100 m, and 200 m events.

Comparison of temporal characteristics between the 100 m and 200 m event revealed multiple differences. For both male and female athletes, the 100 m event was characterised by an increase in total pull time, total kick time, propulsive kick time, kick delay and total movement time, as well as decreases to pull delay, recovery kick time, passive kick time and glide time. The reduction in passive phases (pull delay, passive kick and glide) throughout the stroke cycle in the 100 m event reflected a shift towards a continuous or overlapped mode of coordination (Chollet et al., 2004). This finding is consistent with much of the existing literature that has reported reductions to time spent in arm glide, leg glide and total glide phases during the 100 m event when compared to the 200 m (Chollet et al., 2004; Takagi et al., 2004). In the present dataset, reductions to the percentage of time spent in passive phases and the recovery kick phase were coupled with increases to total pull, total kick, propulsive kick and total movement phases. This pairing indicates that swimmers elected to minimise passive phases associated with deceleration and maximise movement phases associated with acceleration when swimming the 100 m event in order to maintain a higher average velocity. Coaches should consequently work with athletes to reduce glide time and recovery kick time when training for the 100 m event. This may be done by beginning the subsequent lateral hand movement earlier after kick completion and activating bicep femoris early in the kick recovery phase (Olstad, Zinner, et al., 2017).

An additional temporal difference was observed between the 100 m and 200 m event in male swimmers. Within this sub-group, the 100 m stroke was characterised by an increase to the percentage of total pull time spent in propulsive pull and a reduction to the percentage of time spent in the recovery pull phase. A similar trend was observed in female swimmers; however, this did not reach statistical significance. The increase to time spent in propulsive pull during the 100 m supports previous reports that swimmers elect to maximise the time spent in propulsive phases and minimise the time spent in recovery and passive phases during this event in order to maximise average velocity. The impact of increased propulsive time on physiological cost is currently unknown. Further investigation in this area would broaden understanding of the physiological cost in elite breast- stroke swimming and provide better understanding of how physiological constraints influence temporal patterns adoption in elite breaststroke swimming. Despite the need for further investigation in this area, the large number of temporal differences identified between the 100 m and 200 m event for both male and female athletes highlighted a need to tailor training programmes specific to a swimmer’s preferred race distance.

Comparison of temporal characteristics between male and female athletes revealed several significant differences. Across both 100 m and 200 m distances, sex-based differences were observed across all temporal parameters with the exception of total kick time and passive kick time. These parameters were only deemed significantly different between male and female athletes during the 200 m event. This finding is consistent with much of the existing literature that has identified sex-based differences during the pull propulsive, kick propulsive and glide phases across both 100 m and 200 m events (Leblanc et al., 2005). Sex-based differences to propulsive delay may be accounted for by differences to both pull and kick recovery phases. At both 100 m and 200 m distances, males spent less time in recovery phases and were consequently able to reduce the amount of passive time spent between propulsive phases. As recovery phases are associated with a period of deceleration, the ability of male swimmers to reduce the time spent in this phase may indicate a reduced velocity minimum at this point (Leblanc et al., 2006). This idea is yet to be investigated within the literature, although warrants further investigation in order to better understand the influence of propulsive delay length on velocity patterns in elite breaststroke swimming.

Sex-based differences in propulsive time and glide time may also be partially attributed to morphology differences between male and female athletes. At both 100 m and 200 m race distances, males spent a greater percentage of total pull and total kick time in propulsive phases. This observation may be accounted for by the increased size and consequent larger propelling surface area of male swimmers (Oxford et al., 2017). At both 100 m and 200 m distances, females spent a larger percentage of total stroke time in glide phases when compared to male swimmers. This difference may be attributed to an increased amount of adipose tissue typical to female morphology (Leblanc et al., 2010; Seifert & Chollet, 2005). Increased adipose mass reduces the energy cost of maintaining the horizontal position associated with the glide phase

(Leblanc et al., 2010; Seifert & Chollet, 2005). Due to the increased energy cost for male swimmers to maintain this position, males may instead choose to minimise glide time and utilise a continuous or overlapped mode of coordination. In response to the described sex-based differences at both 100 m and 200 m distances, it is necessary to tailor training programs to reflect the unique temporal patterns typical of male and female athletes. In response to sex-based differences coaches may choose to ensure glide efficiency is maximised in their female athletes through the maintenance of a horizontal streamlined body position that minimises frontal resistance. Conversely, focus could instead be given to maximising mechanical efficiency throughout the propulsive pull phase to make use of the increased propelling surface area of male athletes in effort to improve performance.

Regression analysis produced different models for each sub-group. Despite statistical difference between models, several parameters were included in multiple models. In response to the statistical difference of each model the second hypothesis was considered partially accepted. One characteristic common to the predictive model of all four sub- groups was the inclusion of propulsive pull time. This was indicative of its importance to overall race time irrespective of sex and race distance. The importance of propulsive pull time to breaststroke performance is consistent with findings of Leblanc et al. (2006) that reported elite swimmers travelled the greatest distance during the arm propulsive phase when compared to all other stroke phases. This pattern was true when expressed in absolute and relative values and across 50 m, 100 m and 200 m race distances (Leblanc et al., 2006). In response to findings of the current study and existing knowledge, it is suggested that time spent in propulsive pull should be considered in the development of elite training programs for both male and female athletes, and 100 m and 200 m swimmers.

The small amounts of variance explained by the female 100 m, female 200 m and male 200 m predictive model suggests a large amount of individual variance between swimmers in these sub-groups. Investigation into additional individualised metrics including velocity profiles and anthropometrics is required in order to identify athlete trends and better understand elite breaststroke swimming from a holistic approach. The limited amount of variance explained by each model further suggests that breaststroke timing is highly individualised and is most likely optimised by the individual to make use of their strengths. Consequently, coaches and sports science practitioners should consider individual attributes during training prescription.

Dissimilar to the remaining sub-groups, the male 100 m predictive model explained a comparatively large amount of variance in overall race time. Together, percentage of total pull time spent in propulsive pull, percentage of total kick time spent in propulsive kick and percentage of total stroke time spent in the glide phase accounted for 49.8% of variance in overall race time. In response to this finding, focus should be given to the maximisation of time spent in arm propulsion and leg propulsion. While glide time was identified as an important parameter in the regression model, due to its weak negative correlation to overall time, it should be considered as a secondary parameter.

Whilst results of this study provide insight into the temporal patterns utilised in elite breaststroke swimming competition several limitations of the investigation must be acknowledged. One such limitation is the evaluation of breaststroke swimming performance using total race time. Incorporating both free swimming and skill components, the use of total race time as a performance parameter prevented direct evaluation of the associations between temporal parameters and the race component to which they are most closely associated, free swimming. Future research investigations into the temporal patterns utilised during elite breaststroke swimming competition should seek to distinguish free swimming and skill components of a race to enable the evaluation of associations between temporal patterns and free swimming speed. It should also be acknowledged that the analysis of temporal patterns in isolation of other performance variables oversimplifies the complexity of elite breaststroke swimming performance. Future research should seek to incorporate additional performance variables including muscle activation patterns, intra-cyclic velocity variations and pacing characteristics into analysis to provide a more holistic understanding of breaststroke performance and an understanding of how these variables influence observed temporal patterns. To further increase the accuracy to which temporal patterns can be identified future investigation of temporal patterns may also consider the inclusion of additional camera views for more accurate analysis of out- and in-sweeping motions characteristic of breaststroke swimming.

3.6 Conclusion

This study developed a novel way to analyse breaststroke temporal patterns. Improving on the ecological validity of existing temporal pattern assessment methods, which have been conducted using 25 m paced efforts, the analysis method developed for use in the present study can be used in future as a reliable method of temporal pattern assessment in competition. Significant temporal pattern differences between sub-groups in competition highlight the need to consider athlete sex and race distance preference in the development of training programs to ensure programme specificity. Despite several group-based similarities in temporal patterns, findings from regression analyses suggest that observed trends may not be applicable to all athletes. Temporal analyses may consequently be better investigated on an individual basis with consideration of individual attributes including anthropometry and strength. The investigation of breaststroke swimming in this manner will provide a holistic understanding of elite breaststroke swimming and allow stronger conclusions to be drawn regarding the role of temporal patterns on breaststroke performance.

Chapter Four: Hand, Knee and Foot Path Patterns in Elite Breaststroke Swimmers and their Association to Velocity at 100 m Pace

This chapter includes a co-authored paper that has been submitted for publication. The bibliographic details of the co-authored paper, including all authors, are:

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My contribution to the paper involved study conception and design, data collection, data analysis and interpretation, and manuscript preparation.

(Signed) ___________________________________ (Date) 17/10/2023.
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(Countersigned) _____________________________ (Date) 17/10/2023.
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Supervisor: Dr. Clare Minahan

Hand, Knee and Foot Path Patterns in Elite Breaststroke Swimmers and their Association to Velocity at 100 m Pace

4.1 Abstract

Technical solutions that result in maintenance of high average velocity are imperative to performance in elite breaststroke swimming. The present study investigated such technical solutions through description of the associations between hand, knee and foot path, and swimming velocity in elite breaststroke swimmers at 100 m pace. Estimates of the three-dimensional position of the hand, knee and foot were derived for eleven elite breaststroke swimmers and used to calculate the total distance travelled, maximum lateral position and relative lateral position of the hand, knee and foot throughout various phases of the stroke cycle. Associations between total hand displacement (insweep) and average velocity (total stroke cycle), total hand displacement (outsweep) and average velocity (insweep), maximal lateral hand position and average velocity (insweep), and the relative position of the hip, knee and foot and average velocity (total stroke cycle) were reported as significant associations. Based on reported findings it was recommended that swimmers utilise the outsweep phase to set up a large path to be travelled by the hand throughout the insweep phase, and achieve relative proximity of the hip, knee and foot along the lateral axis at the beginning of kick propulsion to maintain higher average velocity across the stroke cycle.

4.2 Introduction

Breaststroke swimming is characterised by underwater limb recoveries, a full-body glide phase and two discontinuous propulsive phases (Leblanc et al., 2006; Seifert et al., 2011; Takagi et al., 2004). These characteristics result in breaststroke being associated with the lowest average velocity and highest intracyclic velocity variation (IVV) of the four competitive strokes (breaststroke, butterfly, backstroke and freestyle) (Leblanc et al., 2005; Maglischo, 2003; Seifert et al., 2011). Despite association with the slowest average velocity of the competitive strokes, average swimming velocity remains the strongest correlate with overall performance time in 100 m and 200 m breaststroke events (Thompson et al., 2000). Movement patterns that produce high average velocity are consequently imperative to successful race performance.

The typical time-velocity profile of the hip throughout breaststroke cycle is characterised by two maxima and two minima (Figure 4.1). Beginning with the initiation of arm propulsion, velocity increases to a local maximum that coincides with the end of arm propulsion. Velocity subsequently decreases throughout the arm- and leg-recovery phases before reaching a local minimum at maximal leg flexion. Following this local minimum, there is a second increase in velocity to a local maximum that is associated with the leg propulsion phase. At the end of the leg propulsion phase velocity again decreases to reach its second local minimum that occurs immediately prior to the initiation of the next arm propulsion (Leblanc et al., 2006). With consideration of this pattern, an increase to average velocity across the stroke cycle can be achieved through a velocity increase during one or more of these acceleration or deceleration phases. Technical parameters of the stroke that can manipulate velocity characteristics include temporal patterns, hand and feet trajectory patterns, and body segment velocities.

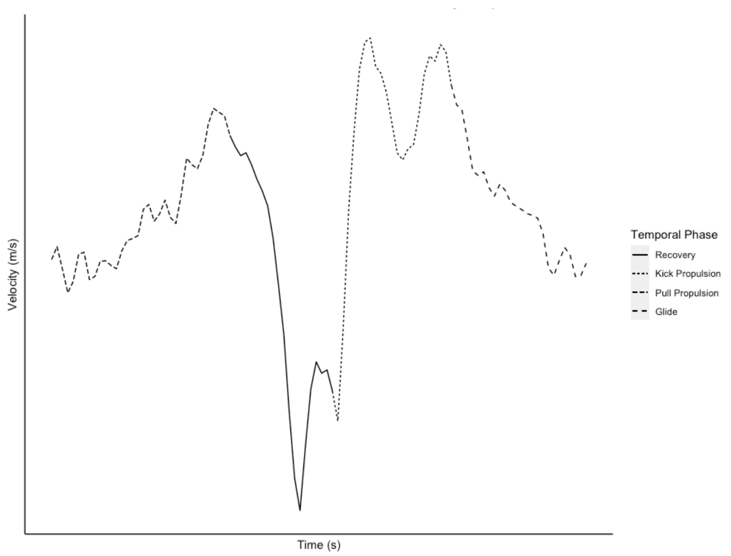


Figure 4.1. Typical Time-Velocity Curve of the Hip Across the Breaststroke Stroke Cycle.

Of the technical parameters that can be manipulated to maximise average velocity in breaststroke swimming, temporal patterns are most frequently investigated. Temporal phases in breaststroke swimming are typically described in relation to movement of the upper or lower limb and to the direction of travel (ie. propulsion, recovery or passive/glide) (Takagi et al., 2004). Description of temporal phases in this way results in definition of between five and ten phases within the stroke cycle (Nicol et al., 2022). Consistent temporal pattern differences have been reported between 50 m, 100 m and 200 m events. Temporal patterns adopted during a 50 m event, when compared to the 200 m event, are characterised by an increase in arm propulsion (additional 3.7% for males and 4.3% for females), decrease in arm glide (reduction of 5.8% for males and 10.2% for females) and an increase in leg propulsion (additional 2.8% for males and 3.4% for females) (Leblanc et al., 2005). These differences in temporal patterns as a function of event distance were also consistently observed when comparing 100 m and 200 m events (Nicol et al., 2021) and reflect a technical solution identified by swimmers to maximise the amount of time spent in propulsive phases during 50 m and 100 m events to maintain higher average velocity when compared to the 200 m event (Nicol et al., 2021).

Analysis of breaststroke temporal patterns also includes the evaluation of a series of coordination parameters. These parameters define the time spent between various stroke phases (Table 4.1). Coordination pattern differences between 50 m, 100 m and 200 m events most frequently occur at T1, the time between the end of leg propulsion and the beginning of arm propulsion (Seifert & Chollet, 2005). This difference reflects a shift towards continuous and overlapped modes of coordination throughout 50 m and 100 m events (Seifert & Chollet, 2005) and again supports the use of a technical solution that maximises time spent in propulsive phases, whilst minimising time spent in recovery and passive phases during shorter breaststroke swimming events. Between-event coordination differences have also been reported during drag (Nicol et al., 2021) and simultaneous recovery time phases (Takagi et al., 2004), however the reported effect of these coordination differences on performance was inconsistent. Given the association of drag and simultaneous recovery time phases to periods of deceleration and velocity minima, it is theoretically expected that a consistent trend in the reduction of time spent in these phases at shorter race distances would be observed with further investigation. Coordination of stroke phases in this way increases average swimming velocity during breaststroke sprint events and supports the higher swimming speeds typically observed during 50 m and 100 m events.

In contrast to temporal patterns, little is known about the relationship between trajectory patterns of the hands and feet and breaststroke velocity patterns. Trajectory patterns of the hand have previously been associated with propulsive characteristics in freestyle and backstroke (Cohen et al., 2015; Gonjo et al., 2021). Hand trajectories have also been used to identify kinematic differences within and between strokes. These include differences between breathing and non-breathing strokes in freestyle (McCabe et al., 2015) and drill swimming and full freestyle swimming (Brackley, 2020). Velocities at various parts of the butterfly stroke, specifically horizontal hand velocity at insweep and outsweep, and vertical foot velocity at the second downbeat have been associated with reductions in IVV (Barbosa, Fernandes, Morouco, et al., 2008). Additional associations have also been made between average swimming velocity and vertical foot velocity during the first downbeat, vertical hand velocity during the insweep and horizontal hand velocity during the insweep (Barbosa, Fernandes, Morouco, et al., 2008). Associations between trajectory patterns, segmental velocities, average swimming velocity and other stroke kinematics have provided insight into how stroke mechanics can be changed to increase average swimming velocity in freestyle, backstroke and butterfly swimming. However, associations between these parameters in breaststroke swimming remain unclear.

Given the above-described mechanical differences of breaststroke swimming to the remaining competitive strokes, findings from the existing knowledge cannot be generalised to breaststroke swimming. The present study sought to address this gap within the knowledge base through the investigation of breaststroke kinematics in elite swimmers using three-dimensional video-based analysis. The aim of this study was to describe the associations between hand, knee and foot path, and swimming velocity in elite breaststroke swimmers at 100 m pace. It was hypothesised that increased total displacement of the hand and foot throughout the stroke cycle, and greater maximal position of the hand and foot along the lateral axis would be associated with higher propulsive velocity (average velocity reached throughout the propulsive pull and propulsive kick phases of the stroke cycle) in elite breaststroke swimmers at 100 m pace. This association was theoretically expected as consequence of an increased amount of time over which force could be applied on the water in the direction of travel. It was also hypothesised that the relative position of the hip, knee and foot at the beginning of propulsive kick would be associated with propulsive kick velocity (average velocity reached throughout the propulsive kick phase of the stroke cycle) at this same pace.

Table 4.1. Coordination Parameters Described in Chollet et al. (2004), Nicol et al. (2022) and Takagi et al. (2004) Breaststroke Models.

Time Period	Chollet et al. (2004)	Nicol et al. (2022)	Takagi et al. (2004)
Time between the end of leg propulsion and beginning of arm propulsion	$T1_a$	Glide	Simultaneous propulsion time
Time between the end of leg insweep and beginning of arm propulsion	$T1_b$		
Time between the beginning of arm recovery and the beginning of leg recovery	T2		
Time between the end of arm recovery and the end of leg recovery	T3	Drag	
Time between 90° arm flexion during recovery and 90° leg flexion during recovery	T4		
Time between the beginning of leg propulsion and the beginning of arm propulsion			Percent arm lag time
Time between the end of arm propulsion and the beginning of leg propulsion		Propulsive delay	Simultaneous recovery time
Time between the beginning of arm propulsion and the beginning of kick recovery		Kick delay	

4.3 Materials & Methods

4.3.1 Participants

Swimmers were required to be of a national semi-final standard or higher and specialise in breaststroke swimming to be eligible for participation in the present study.

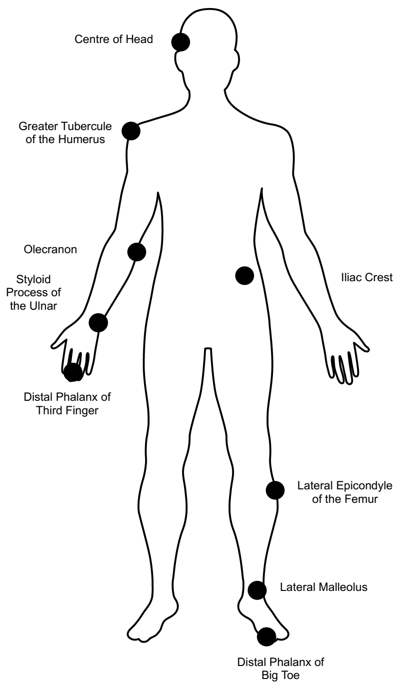
Participants were also required to have achieved a minimum of 800 Fédération Internationale de Natation (FINA) points in their preferred breaststroke race distance (100 m or 200 m) during the 2019, 2020 or 2021 swimming seasons. This points-based cut off restricted sample selection to swimmers within approximately 10% of the existing world record in their preferred breaststroke event. The final inclusion criterion for the present study was the absence of injury at the time of data collection. Eleven elite breaststroke swimmers, five female and six male swimmers, who met the inclusion criteria volunteered to participate in the present study (μ ± one standard deviation age = 22 ± 3 years; height = 182.3 ± 9.6 cm; mass = 76.03 ± 11.45 kg; FINA point score = 870 ± 57). Participants provided written informed consent prior to participation and ethical clearance for conduction of this study was provided by the Griffith University Ethics Committee (GU reference number: 2019/464).

4.3.2 Testing Protocol

Prior to test commencement the position of nine anatomical landmarks were marked on each participant (Figure 4.2). These anatomical landmarks were selected based on their previous use in 3D kinematic research in aquatic environments (Brackley, 2020; Psycharakis et al., 2010; Sanders, Fairweather, et al., 2015). Anatomical landmarks of the humerus greater tubercule, olecranon, ulnar styloid process, iliac crest, femur lateral epicondyle and lateral malleolus were marked with a 4 cm circular, battery-powered, waterproof light-emitting diode (LED) and affixed with Tensospray® and sports strapping tape to ensure they remained in place. Anatomical landmarks at the centre of the head, third finger distal phalanx and first distal phalanx of the hallux were marked with black cloth tape. Due to constraints associated with the testing pool, markers were placed only on the left side of the body and bilateral symmetry of motion was assumed. Swimmers were subsequently provided time to complete a self-selected warm up of up to 15 minutes prior to test commencement.

Breaststroke kinematic data were derived from a 25 m swimming effort performed at each individual's 100 m pace. All testing was conducted in an indoor 25 m pool of 1.2 m – 2.1 m in depth and athletes were instructed to begin from the deep end of the pool.

Video footage of all swimming trials was captured from nine stationary cameras (five below- and four above-water) at 50Hz. Three below-water cameras (Barlus UW-S2Z-C6X25, Shenzhen Zhiyong Industry Co) were mounted using a tri-suction cup mount and the remaining two below-water cameras mounted using wall brackets. Above-water cameras (Canon XF100 HD Professional Camcorder, Canon Australia) were mounted using free-standing tripods. All cameras were positioned to provide differing views and angled towards the calibration structure to ensure the entire intended capture volume was in the centre of field of view (Figure 4.3). Cameras were positioned in this manner to maximise likelihood that anatomical makers would be visible by a minimum of two cameras at any given time. This then enabled the use of triangulation for the estimation of 3D position. Prior to the commencement of each trial a pair on synchronised LEDs visible from all cameras were activated. The first frame that these LED signals appeared to each camera was subsequently used to synchronise all cameras during post-processing.



**Note*. Only the left side of the body was instrumented for this study.

Figure 4.2. Body Marker Placement.

The intended capture volume was 7.5 x 1.8 x 1.5 m along the *x*-, *y*- and *z*- axes respectively and positioned 5 m from the finishing end of the pool (Figure 4.3). The *x*-

axis positive corresponded to progression in the direction of travel, the *y*-axis positive corresponded to vertical movement skyward and the *z*-axis positive to right lateral movement. Prior to data collection the intended capture volume was calibrated in line with processes described by (Abdel-Aziz et al., 2015). A total of 48 above- and 60 below-water control points marked at 0.25 m intervals along the vertical axes of a rigid calibration frame were used to determine linear relationships between 2D pixel coordinates in image frames (ie. camera view) and 3D coordinates within the real-world frame of reference. At the time of volume calibration, no additional structures or persons were in the water to minimise water disturbance and increase calibration accuracy. Following collection of still images required for calibration, the calibration frame was disassembled and removed from the testing space to prevent interference with swimming technique.

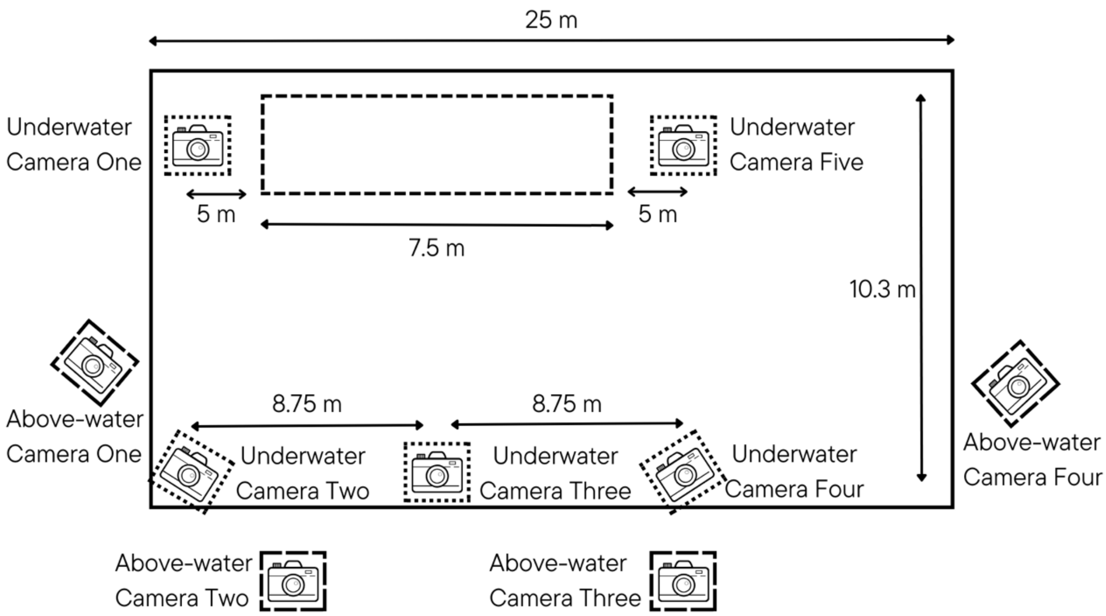


Figure 4.3. Schematic of Camera Placement in the Testing Pool.

4.3.3 Data Analysis

A mixed-methods approach consisting of manual and semi-automated neural network digitisation was used to track body landmarks in the below-water calibration space. Three separate neural networks were trained using DeepLabCut™ (DLC) (v 2.2.3) (Mathis et al., 2018), for underwater cameras two, three and four (Figure 4.3). In accordance with methods described by Papic, Sanders, et al. (2021) and Cronin et al. (2019), neural network training involved the random extraction of 400 video frames per network to define the training datasets: 40 video frames from a single trial of 10 swimmers. The nine marked body landmarks were digitised manually in each frame of the training datasets using the DLC interface. Neural networks (ResNet-50) were then trained in Google Collaboratory using a virtual GPU for 200,000 iterations. Neural networks trained using DLC and following this method have been shown to have high reliability and digitisation accuracy compared with a human operator in below-water environments (Papic, Sanders, et al., 2021). Digitisation accuracy of the models was evaluated using residual analysis and calculated at 1.72 pixels and 1.64 pixels along *u*- and *v*- image axes respectively for landmarks at the third finger distal phalanx, ulnar styloid process, olecranon, iliac crest, lateral epicondyle of the femur, lateral malleolus and hallux distal phalanx. This equated to 0.73 cm and 0.70 cm within the real-world frame of reference along the horizontal and vertical axes respectively. Digitisation accuracy at the centre of the head and greater tubercule of the humerus was lower than other body landmarks due to frequent marker occlusion. Head and greater tubercule of the humerus markers were consequently digitised manually for all trials, as was video footage from underwater cameras one and five after preliminary analysis identified neural network model accuracy was low from these camera views.

The relationship between digitised 2D coordinates and their corresponding position within the real-world frame of reference was subsequently calculated using direct-linear transformation (DLT) (Abdel-Aziz et al., 2015). DLT is the most widely used reconstruction algorithm for 3D motion analysis in aquatic environments (Kwon & Casebolt, 2006; Payton & Burden, 2017). Reconstruction errors of the intended capture volume were 1 mm, 2 mm and 0 mm along the *x*, *y* and *z* axes respectively. Reported reconstruction errors fell within previously accepted limits for video-based kinematic analysis in swimming (Figueiredo et al., 2011). Reconstructed coordinates for each body landmark were assessed for errors across *x*-, *y*- and *z*-axes via visual inspection of data plots. Outliers were removed from the coordinate dataset as required and missing points were interpolated using a cubic spline. Reconstructed coordinates were subsequently smoothed using a 4^{th} order Butterworth low-pass filter with a 6 Hz cut off frequency (Komar, Sanders, et al., 2014; Seifert, Komar, Barbosa, et al., 2014; Takagi et al., 2004). Filtered data were then used to estimate the position of geometric hand, knee and foot segment centres using Visual3D Professional (Version 4.91.0, C-Motion Incorporated, Maryland, USA). Positional data of each segment centre was used for all subsequent analysis. Position data of the hand, knee and foot were initially transformed from real-world reference to the origin of each landmark at the beginning of the stroke cycle. Origin-referenced position data were subsequently used to calculate maximum displacement along the lateral axis (z-axis), total 3D displacement, and the relative lateral position of hand, knee and foot landmarks. Positional data of the hip were also used to calculate instantaneous hip velocity across the stroke cycle in the direction of travel. Average and maximal hip velocity were subsequently calculated during the propulsive pull, outsweep, insweep and propulsive kick phases.

To ensure comparability between individuals, kinematics datasets were shortened to a single stroke cycle. In accordance with definition by Nicol et al. (2021), the stroke cycle was defined as the time period between first lateral hand movement of consecutive strokes. Following this definition, full stroke cycles completed within the intended capture volume were separated within the original dataset and a single stroke cycle selected for all subsequent analysis. In the instance that multiple stroke cycles were completed within the intended capture volume, the second stroke cycle was selected for analysis to ensure the athlete was closer to the centre of the intended capture volume. Stroke rate of the selected stroke was assessed during post-processing using equation 4.1 and subsequently compared to individual race data to ensure the assessed stroke was completed at a SR within ± 5 of the average SR used by each individual during their best 100 m breaststroke race time within the preceding season.

$$SR = 60/[time\ of\ first\ lateral\ hand\ movement\ of\ stroke\ n - time\ of\ first\ lateral\ hand\ movement\ of\ stroke\ (n-1)] \quad (4.1)$$

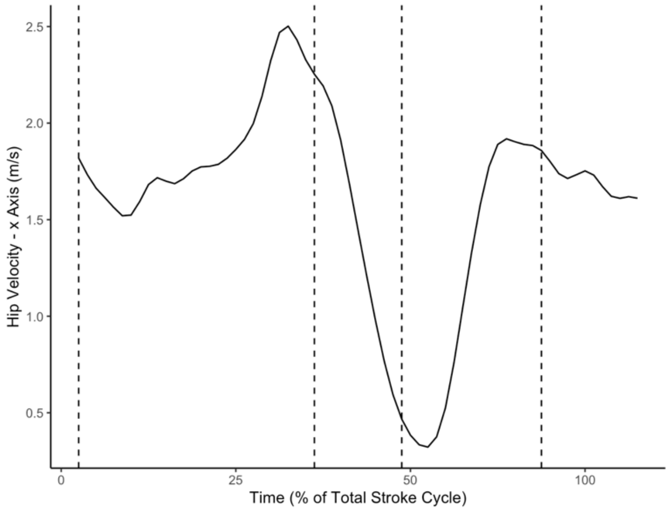
Temporal definitions of Nicol et al. (2021) were also used to identify the time at which the end of propulsive pull, start of propulsive kick and end of propulsive kick occurred within the stroke cycle. To this phasic model two additional temporal phases, pull outsweep and pull insweep, were included. These temporal phases occurred sequentially within the stroke cycle and together comprised the propulsive pull phase. The end of the outsweep phase and beginning of the insweep phase was defined by the instant at which the hands reached the widest point during the pull (Sanders, Fairweather, et al., 2015).

4.3.4 Statistical Analysis

Statistical analysis was completed using R Studio (Version 2023.06.0+421, Posit Software, PBC, Boston, USA). Visual inspection of scatterplots pertaining the data found no gender-based clustering across displacement and hip velocity parameters. Data for male and female athletes was consequently analysed together as a single dataset. Descriptive statistics were calculated to examine the variability in hand, knee and foot path patterns between elite breaststroke swimmers at 100 m pace. To further explore the relevance of described hand, knee and foot path patterns, the associations of these parameters to hip velocity was assessed using a series of Pearson’s correlations. In the event that the assumption of normality was violated for a single parameter, as assessed via a Shapiro-Wilk test, Spearman correlations were instead calculated. Correlation coefficient values of $r \leq 0.40$, $0.40 < r < 0.70$ and $r \geq 0.70$ were interpreted as weak, moderate, and strong associations respectively. Correlation effect size was evaluated using Hedges g and 95% confidence intervals calculated to quantify certainty around reported effects.

4.4 Results

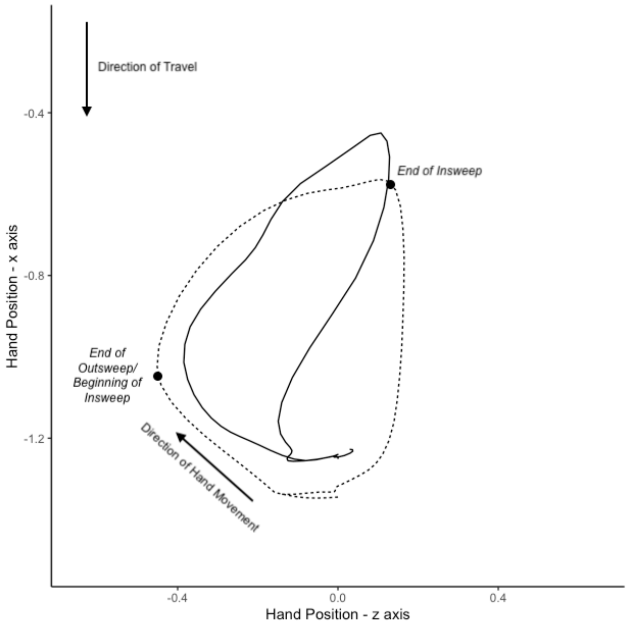
Displacement parameters relating to the hand, knee and foot, and hip velocity characteristics of the propulsive pull phase, propulsive kick phase and total stroke cycle are outlined for each individual in Tables 4.2 and 4.3. Average hip velocity varied between individuals with ranges of 1.52 m/s – 1.89 m/s during the propulsive pull phase, 1.32 m/s – 1.68 m/s during the outsweep phase, 1.77 m/s – 2.19 m/s throughout the insweep phase, 0.88 m/s – 1.27 m/s during the propulsive kick phase and 1.22 m/s – 1.61 m/s across the total stroke cycle. Figure 4.4 provides a graphical representation of the typical time-velocity curve across the stroke cycle with representation of the end of propulsive pull, beginning of propulsive kick and end of propulsive kick phases.



**Note*. Vertical lines represent, from left to right, the time point at the start of propulsive pull, end of propulsive pull, start of propulsive kick and end of propulsive kick. Time-velocity data taken from the dataset of this study.

Figure 4.4. Time-Velocity Curve Across the Stroke Cycle with Representation of Temporal Phases.

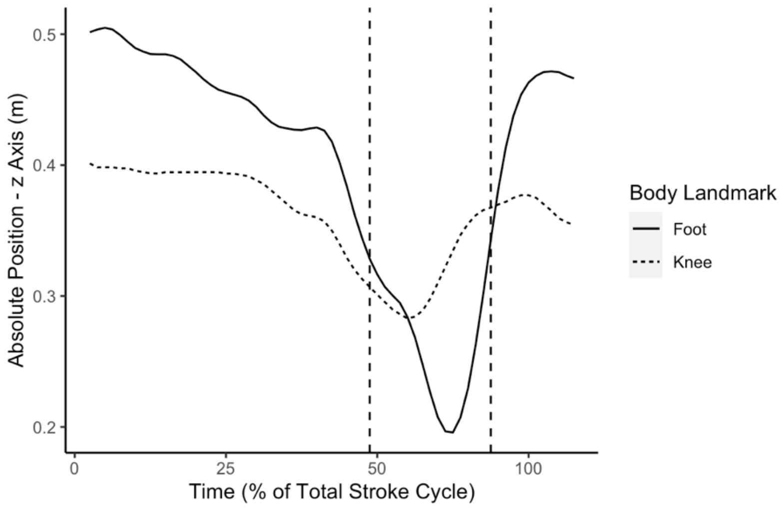
Hand path patterns typically followed a backward, semicircular trajectory as previously described by Maglischo (2013). The propulsive pull phase was initiated with most displacement occurring along the *z*-axis (lateral movement axis). At maximal position along the *z*-axis, the changing point of outsweep and insweep phases, the hands subsequently changed direction to incorporate greater displacement along the *x*-axis (direction of travel axis). Figure 4.5 provides a graphical representation of the typical path travelled by the hand across the stroke cycle. Maximal hand position along the *z*-axis ranged between 0.32 m – 0.60 m for all athletes. Hip velocity patterns across the propulsive pull phase also varied between individuals, however maximal and average velocities were higher during the insweep phase when compared to the outsweep phase for all individuals (μ difference = 0.54 ± 0.15 m/s and μ difference = 0.50 ± 0.14 m/s respectively).



**Note*. Hand position along the *x*-axis displayed relative to hip position. Hand position data taken from the dataset of this study.

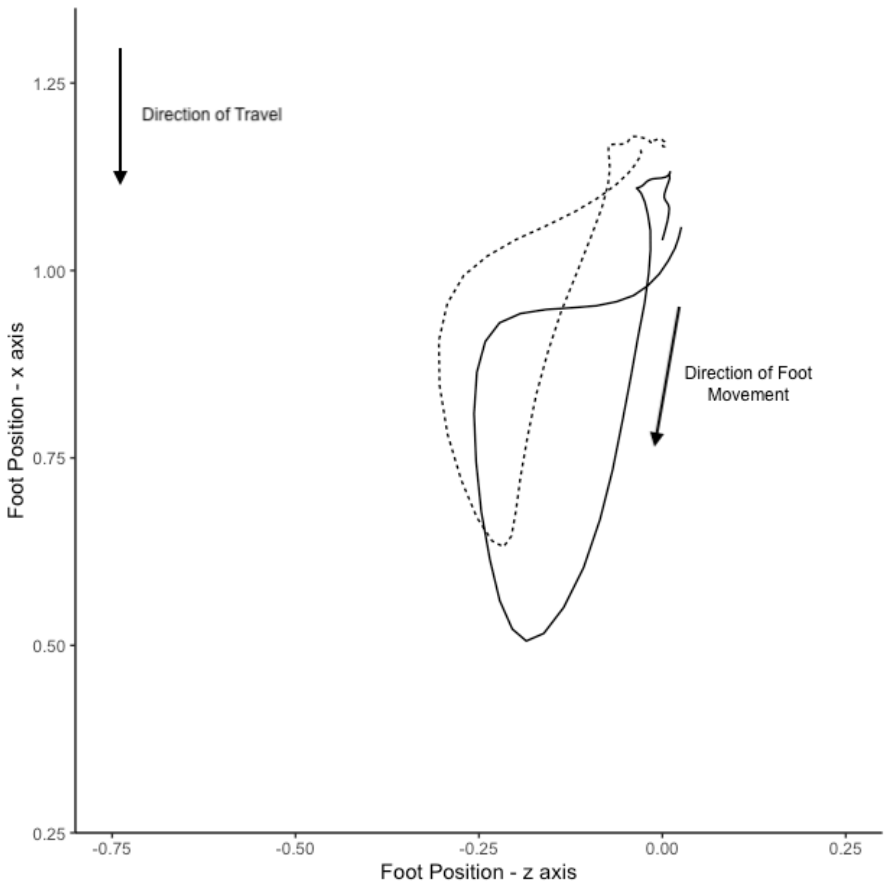
Figure 4.5. Two Participant Hand Paths Followed Along *x*- and *z*- axes Throughout the Stroke Cycle.

Foot path patterns were characterised by maximal, or close proximal distance to maximal knee position (*z*-axis) at the beginning of the propulsive kick phase. Maximal lateral position (*z*-axis) of the knee typically occurred prior to maximal lateral position of the foot (*z*-axis) (Figure 4.6). At their maximal position along the *z*-axis knee and foot position ranged from 0.01 m – 0.29 m and 0.07 m – 0.39 m from their position of origin respectively. At the beginning of the propulsive kick phase the relative position of the knee and foot ranged between -0.12 m and 0.08 m, with the foot typically positioned closer to the midline than the knee. Throughout the propulsive kick phase the feet subsequently followed a semicircular motion before returning to a position close to the origin along *y*- and *z*-axes (vertical- and lateral-axes). Figure 4.7 details the typical path travelled by the foot during the total stroke cycle.



Note. Foot and knee position along the *z*-axis displayed as an absolute position. Vertical lines represent, from left to right, the time point at the start of propulsive kick and end of propulsive kick. Foot and knee position data taken from the dataset of this study.

Figure 4.6. Typical Path Travelled by the Knee and Foot (*z*-axis).



Note. Foot position along the *x*-axis displayed relative to hip position. Foot position data taken from the dataset of this study.

Figure 4.7. Example Foot Paths Followed Along *x*- and *z*- axes Throughout the Stroke Cycle.

Details of the associations between stroke kinematic parameters are provided in Tables 4.4 and 4.5. Moderate to strong associations were frequent between total displacement characteristics of the hand and hip velocity across the stroke cycle. Of the hand displacement parameters calculated, total hand displacement during the insweep was the strongest associate to average hip velocity across the total stroke cycle (r = 0.77) (Figure 4.8). Throughout the propulsive pull phase, no strong associations between segment displacements and average hip velocity kinematics were reported. Further separating the outsweep and insweep phases that comprise the propulsive pull phase however, moderate to strong negative relationships were reported between average hip velocity during the insweep phase and total hand displacement during the total stroke cycle, propulsive pull phase and outsweep phase (r = -0.70, -0.51 and -0.75 respectively). Associations between total hand displacement during the insweep phase and average hip velocity were consistently positive in nature across all temporal phases except for average hip velocity during the insweep phase.

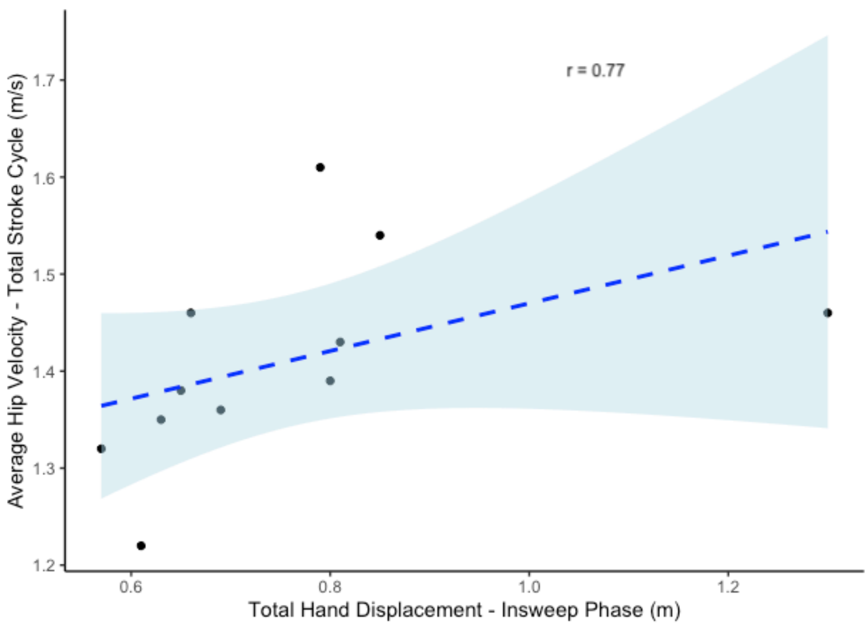


Figure 4.8. Association of Total Hand Displacement (Insweep Phase) and Average Hip Velocity (Total Stroke Cycle).

Associations between maximal hand position (*z*-axis) and hip velocity across the propulsive pull phase, outsweep phase, insweep phase and total stroke cycle were typically weak. A moderate association between maximal hand position (*z*-axis) and hip velocity parameters was observed however, between maximal lateral hand position (*z*-axis) and average hip velocity during the insweep phase (r = 0.64). All other associations were weak, with average hip velocity during the propulsive pull phase (r = 0.25) and maximum hip velocity during the propulsive pull phase (r = 0.24) being the next strongest associates to maximal hand position (*z*-axis).

Associations between hip velocity across the stroke cycle and total foot displacement were consistently negative in nature. The strength of associations between these parameters was typically weak, with the strongest association reported between total foot displacement (propulsive kick phase) and average hip velocity across the total stroke cycle (r = -0.31). The strength of associations between maximal knee position (*z*-axis), maximal foot position (*z*-axis) and hip velocity across the propulsive kick and total stroke cycle were also weak in nature. Moderate to strong associations were frequent however, between the relative lateral position of the hip, knee and foot (*z*-axis) at the beginning of kick propulsion and hip velocity across these phases. Strongest associations between relative position parameters and hip velocity were reported between average hip velocity during the propulsive kick phase and the distance between the hip and knee at the beginning of the propulsive kick phase (r = -0.76), average hip velocity during the total stroke cycle and distance between the hip and knee at the beginning of the propulsive kick phase (r = -0.46), and average hip velocity during the total stroke cycle and distance between the knee and foot at the beginning of the propulsive kick phase (r = -0.32).

Table 4.2. Summary of Hand, Hip, Knee and Foot Displacement Parameters of Elite Breaststroke Swimmers at 100 m Pace.

Athlete	Total Hand Displacement (m)	Maximum Hand Position – *z*-axis (m)	Maximum Knee Position– *z*-axis (m)	Total Foot Displacement (m)	Maximum Foot Position – *z*-axis (m)	Distance Between Hip and Knee at Beginning of Kick Propulsion – *z*-axis (m)	Distance Between Knee and Foot at Beginning of Kick Propulsion – *z*-axis (m)
1	3.38	0.45	0.13	2.95	0.30	-0.10	-0.02
2	3.09	0.51	0.24	2.82	0.39	-0.08	-0.12
3	3.38	0.46	0.09	2.88	0.38	0.08	0.06
4	3.20	0.38	0.22	2.85	0.26	0.13	-0.05
5	4.18	0.43	0.12	2.99	0.25	-0.01	-0.04
6	3.12	0.50	0.29	2.62	0.26	0.05	-0.11
7	4.2	0.60	0.13	3.18	0.22	0.17	-0.11
8	4.34	0.32	0.11	3.69	0.07	-0.05	-0.01
9	5.78	0.34	0.12	3.16	0.17	0.16	-0.05
10	4.80	0.36	0.01	3.67	0.16	0.12	0.08
11	3.55	0.51	0.05	2.90	0.26	-0.08	-0.01

**Note.* The *x*-axis positive corresponded to progression in the direction of travel, the *y*-axis positive corresponded to vertical movement skyward and the *z*-axis positive to right lateral movement.

Table 4.3. Summary of Hip Velocity Characteristics of Elite Breaststroke Swimmers at 100 m Pace.

Athlete	Maximum Hip Velocity During Propulsive Pull Phase (m/s)	Average Hip Velocity During Propulsive Pull Phase (m/s)	Maximum Hip Velocity During Outsweep Phase (m/s)	Average Hip Velocity During Outsweep Phase (m/s)	Maximum Hip Velocity During Insweep Phase (m/s)	Average Hip Velocity During Insweep Phase (m/s)	Maximum Hip Velocity During Propulsive Kick Phase (m/s)	Average Hip Velocity During Propulsive Kick Phase (m/s)	Average Hip Velocity During Total Stroke Cycle (m/s)
1	2.50	1.89	1.82	1.68	2.50	2.19	1.92	1.27	1.61
2	2.24	1.73	1.85	1.59	2.24	2.10	1.52	0.94	1.38
3	2.20	1.56	1.68	1.32	2.20	2.04	1.61	1.03	1.32
4	2.18	1.59	1.45	1.39	2.18	1.90	1.57	0.94	1.35
5	2.40	1.85	1.94	1.68	2.40	2.15	1.82	1.15	1.54
6	2.32	1.74	1.68	1.46	2.32	2.13	1.66	1.08	1.36
7	2.30	1.57	1.67	1.46	2.30	1.95	1.74	0.95	1.43
8	2.14	1.55	1.86	1.44	2.14	1.78	1.67	1.25	1.39
9	2.47	1.65	1.75	1.55	2.47	1.77	2.05	0.92	1.46
10	1.99	1.52	1.54	1.37	1.99	1.84	1.47	0.88	1.22
11	2.29	1.72	1.80	1.52	2.29	2.14	1.83	1.24	1.46

Table 4.4. Correlational Assessment of the Relationship Between Displacement Characteristics of the Knee and Foot, and Hip Velocity.

	Maximum Hip Velocity During Propulsive Kick Phase (m/s)	**Average Hip Velocity During Propulsive Kick Phase (m/s)**	**Average Hip Velocity During Total Stroke Cycle (m/s)**
Maximum Knee Displacement – *z*-axis (m)	r = -0.16, g = -10.97, 95% CI = -14.40 - -7.54	r = -0.13, g = -7.45, 95% CI = -9.87 - -5.04	r = 0.05, g = -12.84, 95% CI = -16.82 - -8.86
Maximum Foot Displacement – *z*-axis (m)	r = -0.18, g = -9.97, 95% CI = -13.10 - -6.83	r = -0.09, g = -6.36, 95% CI = -8.46 - -4.25	r = 0.10, g = -11.17, 95% CI = -14.65 - -7.68
Distance Between Hip and Knee at Beginning of Kick Propulsion – *z*-axis (m)	r = -0.08, g = -11.14, 95% CI = -14.62 - -7.66	**r = -0.76, g = -7.77, 95% CI = -10.27 - -5.27**	**r = -0.46, g = -12.61, 95% CI = -16.52 - -8.70**
Distance Between Knee and Foot at Beginning of Kick Propulsion – *z*-axis (m)	r = -0.15, g = -12.60, 95% CI = -16.50 - -8.69	r = 0.10, g = -9.27, 95% CI = -12.20 - -6.34	**r = -0.32, g = -15.72, 95% CI = -20.55 - -10.89**
Total Foot Displacement (m)	r = -0.11, g = 4.78, 95% CI = 3.10 – 6.46	r = -0.05, g = 7.35, 95% CI = 4.97 – 9.73	**r = -0.28, g = 6.29, 95% CI = 4.21 – 8.38**
Total Foot Displacement – Propulsive Kick Phase (m)	r = -0.21, g = -4.05, 95% CI = -5.55 - -2.56	r = -0.09, g = -1.41, 95% CI = -2.36 - -0.45	**r = -0.31, g = -3.10, 95% CI = -4.37 - -1.83**

**Note.* Relationships of further comment throughout the discussion section have been highlighted.

Table 4.5. Correlational Assessment of the Relationship Between Displacement Characteristics of the Hand and Hip Velocity.

	Maximum Hip Velocity During Propulsive Pull Phase (m/s)	**Average Hip Velocity During Propulsive Pull Phase (m/s)**	**Maximum Hip Velocity During Outsweep Phase (m/s)**	**Average Hip Velocity During Outsweep Phase (m/s)**	**Maximum Hip Velocity During Insweep Phase (m/s)**	**Average Hip Velocity During Insweep Phase (m/s)**	**Average Hip Velocity During Total Stroke Cycle (m/s)**
Total Hand Displacement (m)	r = 0.06, g = 2.60, 95% CI = 1.43 – 3.76	r = -0.31, g = 3.57, 95% CI = 2.19 – 4.95	r = 0.05, g = 3.46, 95% CI = 2.11 – 4.82	r = 0.02, g = 3.85, 95% CI = 2.41 – 5.30	r = 0.06, g = 2.60, 95% CI = 1.43 – 3.76	**r = -0.70, g = 3.03, 95% CI = 1.78 – 4.28**	r = -0.14 , g = 4.00, 95% CI = 2.52 – 5.48
Total Hand Displacement – Propulsive Pull Phase (m)	r = 0.01, g = -0.71, 95% CI = -1.58 – 0.18	r = -0.32, g = 0.53, 95% CI = -0.34 – 1.40	r = 0.23, g = 0.40, 95% CI = -0.46 – 1.27	r = 0.16, g = 0.89, 95% CI = -0.01 – 1.78	r = 0.01, g = -0.70, 95% CI = -1.58 – 0.18	**r = -0.51, g = -0.14, 95% CI = -1.00 – 0.72**	r = 0.21, g = 1.06, 95% CI = 0.15 – 1.98
Total Hand Displacement – Outsweep Phase (m)	r = 0.01, g = -1.46, 95% CI = -2.42 - - 0.49	r = -0.07, g = -0.86, 95% CI = -1.75 – 0.04	r = 0.01, g = -1.46, 95% CI = -2.42 - - 0.49	r = -0.07, g = -0.86, 95% CI = -1.75 – 0.04	r = -0.11, g = -2.86, 95% CI = -4.08 - - 1.64	**r = -0.75, g = -2.14, 95% CI = -3.21 - - 1.06**	r = -0.19, g = -0.64, 95% CI = -1.52 – 0.24
Total Hand Displacement – Insweep Phase (m)	**r = 0.66, g = -8.22, 95% CI = -10.85 - - 5.59**	r = 0.36, g = -5.21, 95% CI = -7.00 - - 3.42	r = 0.48, g = -5.31, 95% CI = -7.13 - - 3.49	**r = 0.64, g = -4.27, 95% CI = -5.82 - - 2.72**	**r = 0.66, g = -8.22, 95% CI = -10.85 - - 5.59**	r = -0.02, g = -6.60, 95% CI = -8.77 - - 4.42	**r = 0.77, g = -3.88, 95% CI = -5.33 - - 2.43**
Maximum Hand Displacement – *z*-axis (m)	r = 0.24, g = -14.49, 95% CI = -18.96 - - 10.02	r = 0.25, g = -10.98, 95% CI = -14.41 - - 7.55	r = 0.10, g = -10.37, 95% CI = -13.63 - - 7.12	r = 0.14, g = -9.72, 95% CI = -12.78 - - 6.66	r = 0.24, g = -14.49, 95% CI = -18.96 – 10.02	**r = 0.64, g = -11.84, 95% CI = -15.53 - - 8.16**	r = 0.18, g = -9.62, 95% CI = -12.65 - - 6.59

**Note*. Relationships of further comment throughout the discussion have been highlighted.

4.5 Discussion

The present study investigated 3D hand, knee and foot path characteristics in a sample of elite breaststroke swimmers at 100 m pace. Analysis of the maximal and total displacement characteristics of key landmarks across the stroke cycle provided further insight into their association to maximal and average swimming velocity at 100 m pace. These insights provided further understanding of the kinematic parameters that mediate swimming performance within an elite breaststroke swimming population.

Investigation of hand paths found several hand displacement characteristics associated with hip velocity across both the propulsive pull phase and the total stroke cycle. Reported associations were in partial support of the hypotheses, with greater pull width and increased total displacement of the hand being associated with higher maximal and average hip velocity across some subphases of the propulsive pull phase and the total stroke cycle. Of the kinematic hand path parameters assessed, total hand displacement during the insweep phase was reported the strongest associate to average hip velocity across the total stroke cycle ($r = 0.77$). This was indicative that swimmers who had a higher total 3D displacement of the hand during this phase maintained a higher average hip velocity across the total stroke cycle. This association is graphically depicted in Figure 4.5, with the hand path represented by a dotted line following a longer path during the insweep phase and being associated with higher average hip velocity across the stroke cycle when compared to the hand path represented by the solid line. The strong association of these kinematic parameters was theoretically expected, given the path of the hand during this phase is described as a backwards, semicircular motion in the same direction as the intended direction of travel (Maglischo, 2013). It can be hypothesised that the increased total hand path during this phase consequently resulted in swimmers having a longer distance to apply pressure on the water in the direction of travel. This would then result in swimmers being able to achieve a higher mean swimming speed.

Associations between hand displacement characteristics during the outsweep phase and average hip velocity across the stroke cycle were comparatively weak in nature. However, moderate to strong associations were reported between hand displacement during the outsweep phase and hip velocity characteristics during the insweep phase.

Throughout this phase maximal hand position along the *z*-axis (lateral movement axis) was positively associated with average hip velocity maintained throughout the insweep phase (r = 0.64). Average hip velocity during the insweep phase was also strongly associated with total hand displacement during the outsweep phase (r = -0.75). In accordance with reported associations, swimmers who reached greater maximal hand position along the lateral axis during the outsweep phase and did so with a more direct hand path maintained a higher average hip velocity during the insweep phase. Given the relatively weak associations of hand displacement characteristics during the outsweep phase to average hip velocity of the total stroke cycle, but strong association of outsweep displacement to average hip velocity maintained during the insweep phase, it is suggested that hand displacement during the outsweep phase acts to set up the hand path travelled and hip velocity achieved during the insweep phase. Given the strong association between total hand displacement during the insweep phase and the average hip velocity maintained during the total stroke cycle, swimmers should consequently use the outsweep phase to set up a large path that can be travelled by the hand during the subsequent insweep phase in order to maintain a higher average hip velocity across the total stroke cycle.

Displacement characteristics of the knee and foot were typically weakly associated with hip velocity throughout the propulsive kick phase and total stroke cycle (Table 4.4). This finding was not in support of the hypotheses, which stated that these kinematic parameters would be associated with hip velocity characteristics across the stroke cycle. The consistent negative association of these parameters also did not support the hypothesis that increased maximal and total displacement of the foot would be positively associated with increased hip velocity across the propulsive pull phase and total stroke cycle.

Of the knee and foot displacement parameters investigated, moderate to strong associations were most frequently reported in reference to the relative position of the hip, knee and foot at the beginning of the propulsive kick phase along *z*-axis (lateral movement axis). At the beginning of this phase the relative position of the hip and knee was strongly associated with average hip velocity throughout the propulsive kick phase (r = -0.76). The relative position of the hip and knee and the knee and foot were also associated with average hip velocity across the total stroke cycle (r = -0.46 and -

0.32 respectively). These negative associations indicated that swimmers who positioned the hip, knee and foot in relative proximity along the *z*-axis, indicating a more vertically aligned position, maintained a higher average hip velocity across the stroke cycle. Given the comparatively weak association of maximal and total displacement characteristics of the knee and foot to hip velocity across the stroke cycle, it is suggested that the relative position of these body markers be of greater importance in the maintenance of hip velocity across the stroke cycle than their absolute position. In extension to this finding, the total displacement of the foot during the propulsive kick phase was negatively associated with average hip velocity across the total stroke cycle ($r = -0.31$). This association signified a trend for swimmers who utilised a shorter foot path during the propulsive kick phase to maintain a higher average hip velocity during the total stroke cycle. Given the nature of the above-described associations, it is suggested that athletes elected to reduce total foot displacement in order to begin the subsequent pull phase sooner and increase stroke rate. This rationale could explain the report of higher average hip velocity (total stroke cycle) achieved by swimmers who followed a shorter foot path throughout the propulsive kick phase, however further investigation into the influence of hand, knee and foot displacement characteristics on stroke rate maintenance in breaststroke swimming is required to confirm this suggestion.

Although findings from the present study have contributed to the body of knowledge that describes breaststroke kinematics in elite populations, it is acknowledged that confidence in drawn conclusions may be limited due to the assessment of single-side kinematics. Due to constraints associated with the testing pool, kinematics on both left and right sides of the body could not be assessed and stroke symmetry was assumed. Analysis of this nature negates the potential influence of stroke asymmetries on hip velocity characteristics across the stroke cycle and should be considered in future research investigations to further understand how 3D displacement of the hand, knee and foot influence hip velocity in breaststroke swimming within elite populations. The use of a single-sided body marker set-up also reduced the accuracy of centre of mass calculation. Hip velocity was consequently used to assess overall movement of the body through space within the present study. Although movement of the hip has frequently been used within the existing literature to assess body movement through space (Colman et al., 1998; Leblanc et al., 2006; Takagi et al., 2004), it has been established that the magnitude of velocity fluctuations at the hip is greater than at the centre of mass in breaststroke swimming (Gourgoulis et al., 2018). Findings of the present study consequently cannot be used to draw conclusions about velocity patterns of the centre of mass in elite breaststroke swimmers.

Based on findings of the present study, the investigation of hand, knee and foot displacement characteristics at 200 m pace is of future research interest. Given previously described temporal differences between 100 m and 200 m events (Nicol et al., 2021) it cannot be assumed the kinematic patterns described within the present study are also applicable to breaststroke swimming during the 200 m event. Further investigation in this area is required to ensure prescribed displacement patterns are event specific and an understanding of how displacement characteristics can be manipulated to improve performance across both 100 m and 200 m events is established.

4.6 Conclusion

Displacement patterns of the hand, knee and foot have association to hip velocity characteristics of elite breaststroke swimmers at 100 m pace. These associations indicate that the outsweep phase of the propulsive pull acts to set up hand path during the subsequent insweep phase. During this outsweep phase swimmers should follow a direct path from the initiation of pull to maximal lateral position to maximise average hip velocity achieved during the subsequent insweep phase. Displacement during the outsweep should also set up a large path that can be travelled by the hand during the insweep phase. This acts to increase the average hip velocity maintained across the total stroke cycle. In relation to foot displacement patterns during 100 m breaststroke swimming, swimmers should aim to achieve relative lateral proximity of the hip, knee and foot at the beginning of kick propulsion and follow a short foot path throughout the propulsive kick phase to achieve higher average hip velocity across the total stroke cycle. Through the application of current findings to the training environment and further investigation into the influence of displacement characteristics on hip velocity in breaststroke swimming it is hoped that hand, knee and foot displacement patterns can be optimised within the training environment to help elite athletes achieve peak performance during the 100 m breaststroke event.

Chapter Five: The Association of Range of Motion, Dryland Strength–Power, Anthropometry, and Hip Velocity in Elite Breaststroke Swimmers

This chapter includes a published, co-authored paper. The bibliographic details of the co-authored paper, including all authors, are:

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My contribution to the paper involved study conception and design, data collection, data analysis and interpretation, and manuscript preparation.

(Signed) ___________________________________ (Date) 17/10/2023.
Student: Emily Nicol

(Countersigned) _____________________________ (Date) 17/10/2023.
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(Countersigned) _____________________________ (Date) 17/10/2023.
Supervisor: Dr. Clare Minahan

The Association of Range of Motion, Dryland Strength-Power, Anthropometry and Hip Velocity in Elite Breaststroke Swimmers.

5.1 Abstract

Purpose: The ability of elite breaststroke swimmers to maximise average velocity maintained throughout a race is reportedly mediated by a number of range of motion, dryland strength-power and anthropometric characteristics. The present study aimed to develop a physical profile and evaluate the relationship between dryland strength-power and stroke kinematic variables in elite breaststroke swimmers. *Methods*: A series of range of motion, dryland strength-power and anthropometric measures were assessed in eleven elite level breaststroke specialists and used to establish group-based averages and expected variance within an elite breaststroke population. *Results:* Analysis of the relationships between dryland strength-power parameters and breaststroke kinematics revealed strong associations ($r > 0.7$, minimum 95% confidence range of $g > 0.80$ or < -0.80) most frequently at 100 m and maximal paces. From further analysis of these associations, a series of second order models of best fit were calculated to describe the relationship between dryland strength-power parameters and propulsive velocity. Five models strongly described the relationship between countermovement jump height, mean pull up velocity and average propulsive velocity. *Conclusions:* These models can be used to assess technical proficiency and act as a catalyst for technique evaluation. It is also recommended that strength and conditioning coaches consider the inclusion of explosive movements, such as countermovement jumps and maximal velocity pull ups, in dryland training programs designed for sprint breaststroke swimmers.

5.2 Introduction

Breaststroke swimming is characterised by discontinuous propulsive phases (Leblanc et al., 2006; Takagi et al., 2004), full-body glide phases and a high level of intra-cyclic velocity variation (Seifert et al., 2011). Elite breaststroke swimmers must consequently be able to optimally coordinate upper and lower limb movements, maintain velocity throughout the body glide phase and overcome a comparatively high amount of inertial force when compared to the remaining competitive strokes, to maximise average velocity throughout a race. Individual technique characteristics employed by an athlete to maximise average race velocity are reportedly dependent on range of motion (ROM), dryland strength-power and anthropometry attributes.

Range of motion has been reported to influence two aspects of breaststroke technique: body undulation and breaststroke kick (Jagomägi & Jürimäe, 2005; Maglischo, 2003; Persyn et al., 2000; Seifert et al., 2011). Body undulation refers to doming and cambering motions that occur throughout each stroke cycle (Colman et al., 2013). The amount of undulation performed throughout the stroke cycle differs between individuals and is highly dependent on trunk ROM, defined as the range or angle of the shoulder and hip relative to horizontal (Persyn et al., 2000). Use of this undulating movement is considered advantageous performance as it reduces intra-cyclic velocity variation and consequently reduces inertial forces which must be overcome to initiate propulsion (Gourgoulis et al., 2018; Leblanc et al., 2006; Seifert et al., 2011). Swimmers with a relatively inflexible trunk must instead adopt a flat style of breaststroke, reliant instead on strength for propulsion (Persyn et al., 2000; Seifert et al., 2011).

Adequate ROM is also important to the execution of a strong breaststroke kick. The kick cycle begins with knee flexion to bring the feet forward and is followed by dorsiflexion and eversion of the feet (Maglischo, 2003). The legs subsequently extend in a circular motion until they are brought together towards the midline (Maglischo, 2003). To produce maximal force throughout the leg extension phase, swimmers must have good internal hip rotation, external knee rotation, dorsiflexion and ankle eversion (Maglischo, 2003). Of these parameters, external knee rotation has been reported as the most important ROM parameter to 100 m kick time (Jagomägi & Jürimäe, 2005). Despite consistent report of the association between ROM and breaststroke swimming performance, normative ROM values in an elite breaststroke population are yet to be established within the literature. Investigation into ROM differences between an elite and a non-elite breaststroke population, and the ROM parameters associated with breaststroke swimming performance have also not yet been conducted. Further investigation in this area would aid understanding of the importance of ROM characteristics to elite breaststroke swimming performance.

Another series of physical attributes associated with breaststroke swimming performance are dryland muscular endurance and power. Similar to the role of ROM, endurance and power are thought to influence stroke style, stroke length (SL) and stroke rate (SR). In a cohort of national-level athletes, swimmers who swam with higher SR when compared to the sample average performed better on an exhaustive pull up test (Invernizzi et al., 2014). In contrast, swimmers who adopted a stroke style with longer SL when compared to the sample average performed better on a countermovement jump test (Invernizzi et al., 2014). Dryland muscular endurance and power capacities however, have not been found to influence breaststroke swimming speed (Invernizzi et al., 2014). This finding contrasts previous report of associations between dryland endurance, dryland power and performance in freestyle swimming. Associations between average velocity, absolute power and relative power during a maximal pull up test (Pérez-Olea et al., 2018), mean propulsive power during a squat jump test (Loturco et al., 2015), maximum mean propulsive power during a lat pull down test (Morouço, Neiva, et al., 2011) and 50 m freestyle swimming performance have previously been reported within the literature. Reason for difference in the strength of established associations between dryland capacities and swimming performance of freestyle and breaststroke events is currently unclear. Given the limited amount of literature that has focused on the association between dryland strength-power measures and breaststroke swimming performance specifically, the present study sought to further investigate how dryland capacities influence breaststroke swimming kinematics in an elite population.

Anthropometry is a third physical attribute commonly associated with athletic performance. Anthropometric parameters such as skinfold thickness (Garcia-Gil et al., 2018), limb length (Garcia-Gil et al., 2018; Zaccagni et al., 2019) and body type (Van der Zwaard et al., 2019) have been associated with performance in elite basketball, sprint running and cycling (Garcia-Gil et al., 2018; Van der Zwaard et al., 2019; Zaccagni et al., 2019). Similar associations are yet to be established within elite breaststroke swimming populations. Further investigation into the anthropometric attributes of elite breaststroke swimmers is of importance given the unique physiological and technical requirements of the stroke.

The present study aimed to address identified gaps within the literature through the development of a physical profile of elite breaststroke swimmers. It also aimed to evaluate the relationship between dryland strength and power, and stroke kinematic variables in male and female athletes. It was hypothesised performance on upper-body dryland power measures would be strongly related to SR and average velocity throughout the propulsive pull phase in breaststroke swimming. It was also hypothesised that performance on lower body dryland strength and power measures would be strongly related to SL and average velocity throughout the propulsive kick phase. The final hypothesis of the present study was that dryland strength and power measures would not be strongly related to glide or recovery stroke phase velocity.

5.3 Methods

5.3.1 Participants

The development of a physical profile for elite breaststroke swimmers was dependent on the selection of a high-performance sample. Participants were at minimum of a national semi-final standard and specialised in breaststroke swimming. For inclusion in the present study swimmers were required to have achieved a minimum Fédération Internationale De Natation (FINA) point score of 800 in their preferred breaststroke event during the 2019, 2020 or 2021 swimming seasons. Eight hundred FINA points was selected as a cut off value to include only swimmers within 10% of the existing world record in their preferred event. Swimmers were also required to have competed at a national level and be free from injury at the time of testing. Eleven elite breaststroke swimmers, six female and five male athletes, volunteered to participate in the study (age μ = 23 years ± 3, height μ = 181.5 cm ± 9.6, weight μ = 74.65 kg ± 11.91, FINA point score μ = 882 ± 37). All participants completed between eight and ten training sessions per week in their daily training environment and provided informed consent prior to participation. Ethical clearance for the conduction of this study was provided by the Griffith University Ethics Committee (GU Ref No: 2020/068).

5.3.2 Methodology

5.3.2.1 Physical Characteristics.

Three areas of testing comprised the physical characteristic assessment: ROM, dryland strength-power and anthropometry. Range of motion assessment was conducted through a physiotherapy screening. Passive ROM was assessed across 11 standards: shoulder abduction internal rotation, thoracic rotation, tibial external rotation, tibial external rotation with hip internal rotation, hip flexors, shoulder external rotation, shoulder internal rotation, hamstrings, ankle plantarflexion, combined elevation and hip internal rotation. Assessment sites were selected based on their inclusion in the ROM assessment battery used in the daily training environment. All assessments were conducted in accordance with testing protocols developed by Harvey et al. (1998) and completed by an experienced physiotherapist with familiarity of swimming ROM assessment.

Dryland strength-power testing consisted of a maximal velocity pull up test (power-based test), countermovement jump test (power-based test) and maximal adductor force test (strength-based test). Tests were selected based on their inclusion in the dryland assessment battery used in the daily training environment. Each test was completed three times with a participant-selected recovery period provided between efforts. The trial of maximal velocity, greatest jump height and maximal force were included in analysis.

The maximal velocity pull up test required participants to complete a single pull up as quickly as possible. Participants were instructed to position their hands shoulder width apart on the overhead bar using a pronated grip and were required to hang stationary prior to commencement of the pull up trial. Average velocity throughout the movement phase was measured using a linear positional transducer (GymAware, Kinetic Performance, Australia) and recorded following the trial. Trials were excluded if the participant was not hanging and stationary prior to test commencement, or the participant's pull did not reach the overhead bar. The countermovement jump test required participants to complete a single countermovement jump, aiming for maximal height. Participants were instructed to start from a standing position and were required to maintain hand placement on their hips throughout the trial. Jumps were conducted on the ForceDecks Dual Force Plate System (VALD Performance, Australia). Force data were subsequently used to calculate jump height in accordance with the impulse-momentum relationship. This method was selected due to the overestimation of jump height when using flight time calculation (Moir, 2008). The adductor strength test required participants to complete one three second maximal effort isometric adductor squeeze. Participants were in a supine position with feet planted and knees bent to 60°. Once positioned, a force plate (ForceFrame, VALD Performance, Australia) was placed between participants' knees and participants were instructed to squeeze as hard as possible for three seconds. The maximal combined force obtained throughout this time was recorded. The reliability of all three methods of measurement have previously been established within sporting populations (Merrigan et al., 2021; Orange et al., 2020; Ryan et al., 2019).

Anthropometric assessment consisted of a series of limb length measurements. Measurements of acromiale-radiale, radiale-stylion, mid-stylion-dactylion, trochanterion height, trochanterion-tibiale-laterale, tibiale-laterale height and foot length were taken in accordance with International Society for the Advancement of Kinanthropometry (ISAK) guidelines. To ensure consistency between measurements a single ISAK accredited practitioner completed all assessments. Two measurements of each length were taken, and the mean of these values used for analysis. In the event of >0.3 cm disparity between measurements at a given site a third measurement was taken, and the median value used for analysis.

5.3.2.2 Temporal and Phase Velocity.

Temporal and phase velocity information was derived from three 25 m breaststroke swimming efforts swum at self-selected 200 m, 100 m and maximal paces respectively. Prior to commencement of the first trial participants were instructed to swim at their average pace throughout the 200 m, 100 m event during competition, and at maximal pace for the final 25 m effort. Participants were also instructed to swim at a consistent SR throughout each effort. Trials were conducted in a 25 m indoor pool of varying depth. Participants commenced all trials from the same end of the pool and were instructed to complete a 25 m active recovery swim between trials.

Temporal information used in the present study provided a measure of the amount of time spent in various phases throughout the stroke cycle. Temporal data was calculated from footage captured on an underwater camera (Barlus UW-S2Z-C6X25, Shenzhen Zhiyong Industry Co, China) positioned perpendicularly to the swimming direction and approximately 9 m from the swimmer. The camera was placed 16 m from the starting end to avoid inclusion of strokes immediately following breakout and recorded at 50Hz. In accordance with methods established by Nicol et al. (2021), six key events were identified during each stroke cycle: start of pull, finish of pull, finish of arm drive, start of kick recovery, start of kick propulsion and finish of kick. These events were subsequently used to determine time spent in propulsive pull, propulsive kick, recovery pull, recovery kick, propulsive delay and drag phases. All strokes in which the swimmer was completely within the camera field of view (between three and five strokes) were analysed and the average time spent in the various stroke phases used for analysis. Stroke rate was calculated using equation 5.1 and average SR across all digitised strokes used for analysis.

$$SR = 60/(time\ of\ start\ of\ pull\ stroke\ n - time\ of\ start\ of\ pull\ stroke\ n-1) \quad (5.1)$$

Swimming velocity was obtained using a linear position transducer (iRex, AMR Sports, Australia) (otherwise referred to as a velocimeter or speedreel) sampling at 2 cm increments. The transducer was attached to participants' swimwear at hip height and swimmers were instructed to swim in line with the device. All swimmers were familiar using a linear position transducer attachment and thus did not require re-familiarisation prior to test commencement. Upon trial commencement the transducer emitted a light signal that was viewable in all camera views. This enabled temporal and hip velocity information to be synchronised, and velocity-time series segmented based on the above-described temporal phase data. This was then used to determine average hip velocity reached during propulsive pull and propulsive kick phases at 200 m, 100 m and maximal paces.

5.3.3 Statistical Analyses

All statistical analyses were conducted using RStudio Version 1.3.1056 (RStudio, Boston, USA). Data were initially grouped into sex-based subsets and individual athlete results screened to ensure average hip velocity progressively increased from 200 m to maximal paced efforts. Individual athlete results were also screened to ensure each trial was completed at a SR that fell within ± 5 of the average SR maintained by each participant throughout their fastest 50 m, 100 m and 200 m competition performance during the preceding season. Subsets were subsequently analysed independently using the same statistical procedures.

Descriptive statistics were used to provide a profile of dryland strength-power, anthropometric and ROM parameters of the sample. Mean values were subsequently compared between male and female subsets using a series of t-tests. In the event that assumptions of normality or homoscedasticity were violated, Welch's t-test was used to compare means.

The relationship between swimming kinematics and dryland strength-power parameters was evaluated using regression analysis (i.e. Pearson's correlations). Correlation effect size was assessed using Hedges' g to limit effect bias resulting from the use of the alternative parameter (Cohen's d) in small samples (Borenstein et al., 2009), and 95% confidence intervals calculated to quantify the certainty around reported effects.

5.4 Results

The physical profile of elite breaststroke swimmers was detailed across 39 performance parameters (Table 5.1). Values reported for male breaststroke swimmers were higher when compared to female breaststroke swimmers across all dryland strength-power parameters, with the exception of maximum adductor force. Range of motion scores were similar between male and female athletes across all measures. Male swimmers had greater limb lengths at all assessment sites when compared to female swimmers. Largest absolute limb length differences occurred at sitting height (97.2 ± 3.1 cm and 90.3 ± 1.6 cm for male and female swimmers respectively), trochanterion height (98.5 ± 4.3 cm and 90.9 ± 3.5 cm for male and female swimmers respectively), and tibiale laterale height (51.8 ± 2.5 cm and 46.0 ± 1.9 cm for male and female swimmers respectively).

Stroke kinematic information is detailed in Table 5.2, and the relationships between stroke kinematics and dryland strength-power parameters are reported in Tables 5.3 and 5.4. Twenty-four strong correlations with large effect were found between kinematic and dryland strength-power parameters ($r > 0.7$, minimum 95% confidence range of $g > 0.80$ or < -0.80). Strong relations were most commonly found between dryland strength-power and kinematic parameters at 100 m and maximal paces ($n = 9$ and 10 respectively). A larger number of strong relationships with large effect were found in female swimmers ($n = 14$) than male swimmers ($n = 10$). A total of eight kinematic parameters were strongly related to mean pull up velocity, 12 were strongly related to countermovement jump height and four were strongly related to maximum adductor force.

Further details about the second order models of best fit calculated to represent the relationship between propulsive hip velocity and dryland strength-power measures are provided in Tables 5.5 and 5.6. The amount of variance explained by each model ranged from <1% to 87%. Five models explained >60% of variance within the dataset: average hip velocity throughout the propulsive pull phase and mean pull up velocity in female athletes at 100 m and maximal paces, average hip velocity throughout the propulsive pull phase and countermovement jump height in female athletes at 100 m pace, average hip velocity throughout the propulsive kick phase and countermovement jump height in female athletes at 200 m pace, and average hip velocity throughout the propulsive kick phase and mean pull up velocity in male athletes at 100 m pace.

Table 5.1 Stroke Rate, Stroke Length and Hip Velocity Characteristics of Elite Breaststroke Swimmers.

Parameter	Male	Female
Number	5	6
Height (cm)	189.9 ± 6.0	173.4 ± 3.6
Body Mass (kg)	86.68 ± 7.78	65.50 ± 3.61
FINA Point Score	861 ± 45	901 ± 16
200 Pace SR (cycle/min)	35.60 ± 4.36	33.85 ± 4.61
100 Pace SR (cycle/min)	46.10 ± 2.25	42.43 ± 6.39
Max SR (cycle/min)	53.00 ± 2.97	46.55 ± 5.04
200 Pace SL (m)	2.16 ± 0.21	2.01 ± 0.21
100 Pace SL (m)	1.81 ± 0.11	1.75 ± 0.16
Max SL (m)	1.62 ± 0.11	1.60 ± 0.08
200 Pace Velocity (m/s)	1.27 ± 0.09	1.12 ± 0.05
100 Pace Velocity (m/s)	1.38 ± 0.08	1.22 ± 0.08
Max Velocity (m/s)	1.43 ± 0.07	1.24 ± 0.08
200 Pace Propulsive Pull Velocity (m/s)	1.41 ± 0.12	1.23 ± 0.07
100 Pace Propulsive Pull Velocity (m/s)	1.57 ± 0.09	1.39 ± 0.11
Max Propulsive Pull Velocity (m/s)	1.64 ± 0.12	1.43 ± 0.09
200 Pace Propulsive Delay Velocity (m/s)	0.67 ± 0.10	0.57 ± 0.11
100 Pace Propulsive Delay Velocity (m/s)	0.70 ± 0.12	0.58 ± 0.07
Max Propulsive Delay Velocity (m/s)	0.68 ± 0.09	0.61 ± 0.12
200 Pace Drag Velocity (m/s)	0.73 ± 0.18	0.52 ± 0.12
100 Pace Drag Velocity (m/s)	0.73 ± 0.33	0.56 ± 0.13
Max Drag Velocity (m/s)	0.61 ± 0.23	0.44 ± 0.21
200 Pace Propulsive Kick Velocity (m/s)	1.54 ± 0.10	1.39 ± 0.09
100 Pace Propulsive Kick Velocity (m/s)	1.61 ± 0.13	1.46 ± 0.09
Max Propulsive Kick Velocity (m/s)	1.59 ± 0.09	1.41 0.09
200 Pace Glide Velocity (m/s)	1.29 ± 0.16	1.22 ± 0.06
100 Pace Glide Velocity (m/s)	1.52 ± 0.07	1.31 ± 0.07
Max Glide Velocity (m/s)	1.52 ± 0.19	1.36 ± 0.10

Table 5.2 Descriptive Results of the Range of Motion, Dryland Strength-Power and Anthropometric Characteristics of Elite Breaststroke Swimmers.

Parameter	Male	Female
Body Mass (kg)	86.68 ± 7.78*	65.50 ± 3.61
Maximum Adductor Force (N)	867.20 ± 119.80	687.96 ± 151.69
Mean Chin Up Velocity (m/s)	1.05 ± 0.10*	0.76 ± 0.17
Countermovement Jump Height (Impulse Momentum) (cm)	43.0 ± 8.2*	30.7 ± 5.1
Abduction Internal Rotation Left (°)	149.4 ± 15.3	151.7 ± 8.2
Thoracic Rotation Left (°)	75.6 ± 7.4	71.3 ± 18.6
Tibial External Rotation Left	50.0 ± 8.2	45.7 ± 9.4
Tibial External Rotation With Hip Internal Rotation Left (°)	88.0 ± 6.7	92.3 ± 13.4
Hip Extension Left (°)	0.8 ± 3.9	-4.3 ± 7.1
Shoulder External Rotation Left (°)	92.5 ± 5.0	91.2 ± 8.8
Shoulder Internal Rotation Left (°)	64.2 ± 18.1	66.7 ± 15.1

Note * denotes p < .05.

Parameter	Male	Female
Hamstring Left (°)	75.0 ± 11.7	85.0 ± 9.5
Ankle Plantarflexion Left (°)	170.8 ± 11.4	174.3 ± 4.9
Combined Elevation (°)	5.2 ± 5.9	4.0 ± 5.6
Hip Internal Rotation Left (°)	38.0 ± 2.2	46.2 ± 9.6
Height (cm)	189.9 ± 6.0*	173.4 ± 3.6
Sitting Height (cm)	97.2 ± 3.1*	90.3 ± 1.6
Acromiale Radiale (cm)	37.3 ± 1.6*	33.4 ± 0.8
Radiale Stylion (cm)	28.2 ± 0.9*	25.3 ± 1.5
Mid Stylion Dactylion (cm)	21.6 ± 1.0*	19.8 ± 0.9
Trochanterion Height (cm)	98.5 ± 4.3*	90.9 ± 3.5
Trochanterion Tibiale Laterale (cm)	47.4 ± 2.5	45.6 ± 2.7
Tibiale Laterale Height (cm)	51.8 ± 2.5*	46.0 ± 1.9
Foot Length (cm)	28.5 ± 0.4*	26.1 ± 1.4

Table 5.3 Correlational Assessment of the Relationship Between Dryland Strength-Power and Stroke Kinematic Parameters in Female Athletes.

		Mean Chin Up Velocity (m/s)	Countermovement Jump Height (cm)	Maximum Adductor Force (N)
Stroke Length (m)	200P	r = 0.18 g = 5.61 95% CI (-0.06 – 11.27)	r = -0.56 g = -8.21 95% CI (-16.19 - -0.24)	r = 0.05 g = -5.25 95% CI (-9.30 - -1.19)
	100P	r = -0.44 g = 5.04 95% CI (0.23 – 9.86)	r = -0.31 g = -7.70 95% CI (-14.57 - -0.83)	r = 0.31 g = -4.48 95% CI (-7.46 - -1.49)
	Max	r = -0.69 g = 5.59 95% CI (-0.15 – 11.32)	r = -0.47 g = -8.20 95% CI (-15.92 - -0.48)	r = 0.19 g = -4.84 g = -4.57 95% CI (-8.29 - -1.37)
Stroke Rate (strokes per min)	200P	r = 0.74 g = 4.50 95% CI (2.65 – 6.36)	r = 0.75 g = 0.55 95% CI (-0.03 – 1.13)	r = 0.22 g = -4.57 95% CI (-7.82 - -1.33)
	100P	r = 0.69 g = 4.41 95% CI (2.43 – 6.40)	r = 0.64 g = 1.69 95% CI (0.67 – 2.69)	r = 0.02 g = -5.01 95% CI (-8.96 - -1.07)
	Max	r = 0.84 g = 4.35 95% CI (2.98 – 5.72)	r = 0.75 g = 2.64 95% CI (1.50 – 3.79)	r = 0.20 g = -4.53 95% CI (-7.79 - -1.28)
Average Hip Velocity – Total Stroke	200P	r = 0.65 g = 1.82 95% CI (0.77 – 2.86)	r = 0.82 g = -2.97 95% CI (-4.04 - -1.90)	r = 0.76 g = -2.62 95% CI (-3.74 -1.51)
	100P	r = 0.82 g = 2.07 95% CI (1.26 – 2.89)	r = 0.88 g = -2.44 95% CI (-3.19 - -1.69)	r = 0.50 g = -3.80 95% CI (-5.98 - -1.61)
	Max	r = 0.87 g = 1.88 95% CI (1.24 – 2.52)	r = 0.89 g = -2.32 95% CI (-3.00 - -1.63)	r = 0.56 g = -3.58 95% CI (-5.54 - -1.62)
Average Hip Velocity – Propulsive Pull	200P	r = 0.31 g = 2.86 95% CI (0.83 – 4.89)	r = 0.51 g = -4.83 95% CI (-7.51 – -2.15)	r = 0.20 g = -4.81 95% CI (-8.24 - -1.38)
	100P	r = 0.69 g = 3.39 95% CI (1.83 – 4.95)	r = 0.66 g = -4.08 95% CI (-6.02 - -2.14)	r = 0.05 g = -5.27 95% CI (-9.35 - -1.18)
	Max	r = 0.68 g = 3.62 95% CI (1.90 – 5.33)	r = 0.67 g = -4.00 95% CI (-5.86 - -2.13)	r = 0.18 g = -4.88 95% CI (-8.40 - -1.36)
Average Hip Velocity – Propulsive Delay	200P	r = 0.53 g = -1.05 95% CI (-1.97 - -0.13)	r = 0.39 g = -5.55 95% CI (-8.96 - -2.13)	r = 0.64 g = -3.23 95% CI (-4.85 - -1.61)
	100P	r = 0.87 g = -0.70 95% CI (-1.15 - -0.26)	r = 0.83 g = -2.99 95% CI (-4.05 - -1.93)	r = 0.60 g = -3.40 95% CI (-5.17 - -1.62)
	Max	r = 0.73 g = -0.77 95% CI (-1.42 - -0.13)	r = 0.50 g = -5.02 95% CI (-7.84 - -2.21)	r = 0.49 g = -3.87 95% CI (-6.13 - -1.61)
Average Hip Velocity – Drag	200P	r = -0.07 g = -1.34 95% CI (-2.89 – 0.20)	r = -0.21 g = -7.75 95% CI (-14.41 - -1.10)	r = 0.22 g = -4.76 95% CI (-8.12 - -1.40)
	100P	r = 0.36 g = -0.61 95% CI (-1.71 – 0.49)	r = -0.02 g = -5.63 95% CI (-10.86 - -0.40)	r = 0.19 g = 3.82 95% CI (-7.07 - -0.56)
	Max	r = -0.40 g = -1.25 95% CI (-3.09 – 0.60)	r = 0.01 g = -7.02 95% CI (-12.89 - -1.15)	r = 0.24 g = -4.09 95% CI (-7.21 - -0.97)
Average Hip Velocity – Propulsive Kick	200P	r = 0.23 g = 3.84 95% CI (1.09 – 6.59)	r = 0.52 g = -4.79 95% CI (-7.43 - -2.15)	r = 0.34 g = -4.40 95% CI (-7.28 - -1.51)
	100P	r = 0.56 g = 3.92 95% CI (1.81 – 6.03)	r = 0.63 g = -4.24 95% CI (-6.33 - -2.15)	r = 0.72 g = -2.85 95% CI (-4.14 - -1.56)
	Max	r = 0.36 g = 3.82 95% CI (1.33 – 6.31)	r = 0.72 g = -3.67 95% CI (-5.25 - -2.08)	r = 0.74 g = -2.73 95% CI (-3.91 - -1.54)
Average Hip Velocity – Glide	200P	r = 0.08 g = 3.00 95% CI (0.57 – 5.42)	r = -0.42 g = -8.21 95% CI (-15.82 - -0.59)	r = -0.35 g = -6.25 95% CI (-11.95 - -0.56)
	100P	r = 0.71 g = 2.76 95% CI (1.48 – 4.04)	r = 0.43 g = -5.24 95% CI (-8.37 - -2.10)	r = 0.25 g = -4.66 95% CI (-7.87 - -1.44)
	Max	r = -0.27 g = 3.69 95% CI (0.28 – 7.09)	r = -0.58 g = -8.55 95% CI (-16.90 - -0.20)	r = -0.25 g = -6.02 95% CI (-11.31 - -0.73)

Note [dark grey] Strong relationship [light grey] Moderate relationship [white] Weak Relationship

Table 5.4. Correlational Assessment of the Relationship Between Dryland Strength-Power and Stroke Kinematic Parameters in Male Athletes.

		Mean Chin Up Velocity (m/s)	Countermovement Jump Height (cm)	Maximum Adductor Force (N)
Stroke Length (m)	200P	r = 0.51 g = 4.85 95% CI (1.92 – 7.77)	r = 0.54 g = -3.87 95% CI (-6.18 - -1.56)	r = 0.64 g = -4.91 95% CI (-7.45 - -2.38)
	100P	r = 0.42 g = 5.70 95% CI (2.00 – 9.39)	r = 0.72 g = -3.04 95% CI (-4.52 - -1.57)	r = 0.41 g = -6.30 95% CI (-10.41 - -2.19)
	Max	r = 0.81 g 4.24 95% CI (2.62 – 5.86)	r = 0.77 g = -2.77 95% CI (-4.00 - -1.53)	r = 0.55 g = -5.49 95% CI (-8.63 - -2.35)
Stroke Rate (strokes per min)	200P	r = -0.29 g = 10.10 95% CI (0.55 – 19.65)	r = -0.22 g = -0.91 95% CI (-2.44 – -0.62)	r = -0.57 g = -9.65 95% CI (-19.73 – 0.44)
	100P	r = 0.11 g = 21.45 95% CI (4.70 – 38.21)	r = -0.04 g = 0.42 95% CI (-0.82 – 1.66)	r = -0.23 g = -8.57 95% CI (-16.53 - -0.61)
	Max	r = -0.52 g = 23.95 95% CI (-0.49 – 48.39)	r = -0.43 g = 1.38 95% CI (-0.57 – 3.21)	r = -0.37 g = -8.92 95% CI (-17.64 - -0.20)
Average Hip Velocity – Total Stroke	200P	r = 0.30 g = 1.82 95% CI (0.23 – 3.40)	r = 0.46 g = -4.24 95% CI (-6.95 - -1.53)	r = -0.07 g = -8.46 95% CI (-15.77 - -1.14)
	100P	r = 0.59 g = 2.78 95% CI (1.14 – 4.42)	r = 0.72 g = -3.03 95% CI (-4.49 - -1.58)	r = 0.27 g = -6.97 95% CI (-11.97 - -1.97)
	Max	r = 0.53 g = 3.31 95% CI (1.27 – 5.35)	r = 0.57 g = -3.74 95% CI (-5.89 - -1.59)	r = 0.32 g = -6.73 95% CI (-11.40 - -2.06)
Average Hip Velocity – Propulsive Pull	200P	r = 0.35 g = 2.60 95% CI (0.62 – 4.57)	r = 0.07 g = -5.52 95% CI (-10.06 - -0.98)	r = 0.05 g = 7.95 95% CI (-14.43 - -1.47)
	100P	r = 0.62 g = 4.18 95% CI (1.95 – 6.41)	r = 0.19 g = -5.15 95% CI (-9.13 - -1.17)	r = 0.34 g = -6.63 95% CI (-11.17 - -2.09)
	Max	r = 0.38 g = 4.23 95% CI (1.34 – 7.13)	r = -0.17 g = -6.14 95% CI (-11.77 – 0.51)	r = 0.16 g = -7.51 95% CI (-13.31 - -1.72)
Average Hip Velocity – Propulsive Delay	200P	r = 0.45 g = -2.97 95% CI (-4.98 - -0.95)	r = 0.50 g = -4.13 95% CI (-6.68 - -1.59)	r = 0.50 g = -5.78 95% CI (-9.25 - -2.31)
	100P	r = 0.54 g = -2.54 95% CI (-4.16 - -0.91)	r = 0.31 g = -4.85 95% CI (-8.32 - -1.39)	r = 0.65 g = -4.86 95% CI (-7.34 - -2.38)
	Max	r = 0.77 g = -2.90 95% CI (-4.17 - -1.64)	r = 0.38 g = -4.60 95% CI (-7.72 - -1.47)	r = 0.72 g = -4.30 95% CI (-6.26 - -2.34)
Average Hip Velocity – Drag	200P	r = 0.75 g = -1.34 95% CI (-2.21 - -0.48)	r = 0.73 g = -2.70 95% CI (-4.12 - -1.28)	r = 0.57 g = -4.58 95% CI (-7.37 - -1.79)
	100P	r = 0.26 g = -0.73 95% CI (-1.99 – 0.53)	r = 0.94 g = -0.80 95% CI (-1.15 - -0.44)	r = 0.10 g = -4.33 95% CI (-8.29 - -0.37)
	Max	r = -0.63 g = -1.38 95% CI (-3.69 – 0.93)	r = -0.92 g = -4.63 95% CI (-10.76 – 1.51)	r = -0.34 g = -4.92 95% CI (-10.35 – 0.51)
Average Hip Velocity – Propulsive Kick	200P	r = 0.33 g = 3.91 95% CI (1.10 – 6.72)	r = 0.44 g = 4.30 95% CI (-7.10 - -1.50)	r = -0.03 g = -8.29 95% CI (-15.32 - -1.26)
	100P	r = 0.12 g = 3.90 95% CI (0.69 – 7.11)	r = 0.72 g = -3.03 95% CI (-4.48 - -1.58)	r = -0.12 g = -8.65 95% CI (-16.30 - -1.00)
	Max	r = 0.53 g = 4.43 95% CI (1.81 – 7.06)	r = 0.46 g = -4.21 95% CI (-6.90 - -1.51)	r = 0.16 g = -7.49 95% CI (-13.26 - -1.73)
Average Hip Velocity – Glide	200P	r = 0.52 g = 1.33 95% CI (0.22 – 2.44)	r = 0.73 g = -3.01 95% CI (-4.43 - -1.59)	r = 0.36 g = -6.55 95% CI (-10.97 - -2.12)
	100P	r = 0.90 g = 4.03 95% CI (2.83 – 5.24)	r = -0.17 g = -7.25 95% CI (-14.36 - -0.14)	r = 0.53 g = -6.38 95% CI (-10.36 - -2.39)
	Max	r = 0.77 g = 1.54 95% CI (0.65 - 2.43)	r = -0.08 g = -6.95 95% CI (-13.52 - -0.39)	r = 0.33 g = -7.61 95% CI (-13.24 – -1.98)

Note [dark grey] Strong relationship [light grey] Moderate relationship [white] Weak Relationship

Table 5.5 Regression Models Describing the Relationship Between Dryland Strength-Power and Propulsive Velocities in Female Swimmers.

Propulsive Phase	Dryland Fitness Test	Pace	R^2	RSE	Model Equation
Pull	Mean Chin Up Velocity	200	0.33	0.08	$y = 0.08x^2 + 0.05x + 1.23$
		100	0.82	0.06	$y = 0.14x^2 + 0.17x + 1.39$
		Max	0.70	0.06	$y = 0.10x^2 + 0.13x + 1.43$
	Countermovement Jump Height	200	0.54	0.06	$y = 0.08x^2 + 0.08x + 1.23$
		100	0.71	0.07	$y = 0.13x^2 + 0.16x + 1.39$
		Max	0.67	0.07	$y = 0.09x^2 + 0.14x + 1.43$
	Maximal Adductor Force	200	0.20	0.08	$y = -0.06x^2 + 0.03x + 1.23$
		100	0.19	0.13	$y = -0.10x^2 + 0.01x + 1.39$
		Max	0.21	0.10	$y = -0.08x^2 + 0.04x + 1.43$
Kick	Mean Chin Up Velocity	200	0.23	0.10	$y = 0.08x^2 + 0.05x + 1.39$
		100	0.34	0.09	$y = -0.03x^2 + 0.11x + 1.46$
		Max	0.13	0.12	$y = -0.01x^2 + 0.08x + 1.41$
	Countermovement Jump Height	200	0.87	0.04	$y = 0.15x^2 + 0.10x + 1.39$
		100	0.39	0.09	$y = 0.01x^2 + 0.12x + 1.46$
		Max	0.67	0.07	$y = 0.09x^2 + 0.16x + 1.41$
	Maximal Adductor Force	200	0.13	0.11	$y = 0.02x^2 + 0.07x + 1.39$
		100	0.53	0.08	$y = -0.02x^2 + 0.14x + 1.46$
		Max	0.56	0.09	$y = 0.01x^2 + 0.17x + 1.41$

Table 5.6 Regression Models Describing the Relationship Between Dryland Strength-Power and Propulsive Velocities in Male Swimmers.

Propulsive Phase	Dryland Fitness Test	Pace	R^2	RSE	Model Equation
Pull	Mean Chin Up Velocity	200	0.12	0.15	$y = -0.01x^2 + 0.08x + 1.41$
		100	0.38	0.10	$y = 0.12x + 1.57$
		Max	0.22	0.15	$y = 0.06x^2 + 0.09x + 1.64$
	Countermovement Jump Height	200	0.04	0.16	$y = 0.04x^2 + 0.02x + 1.41$
		100	0.05	0.13	$y = 0.02x^2 + 0.03x + 1.57$
		Max	0.08	0.16	$y = 0.05x^2 – 0.04x + 1.64$
	Maximal Adductor Force	200	0.13	0.16	$y = 0.08x^2 + 0.01x + 1.41$
		100	0.20	0.12	$y = 0.05x^2 + 0.06x + 1.57$
		Max	0.39	0.13	$y = 0.14x^2 + 0.04x + 1.64$
Kick	Mean Chin Up Velocity	200	0.28	0.12	$y = – 0.08x^2 + 0.06x + 1.54$
		100	0.82	0.07	$y = -0.23x^2 + 0.03x + 1.61$
		Max	0.35	0.10	$y = – 0.05x^2 + 0.10x + 1.59$
	Countermovement Jump Height	200	0.22	0.12	$y = 0.03x^2 + 0.08x + 1.54$
		100	0.58	0.12	$y = – 0.06x^2 + 0.18x + 1.61$
		Max	0.28	0.11	$y = 0.05x^2 + 0.08x + 1.59$
	Maximal Adductor Force	200	0.00	0.14	$y = – 0.01x^2 – 0.01x + 1.54$
		100	0.41	0.14	$y = – 0.16x^2 – 0.03x + 1.61$
		Max	0.03	0.13	$y = 0.01x^2 + 0.03x + 1.59$

5.5 Discussion.

The present study provides an updated profile of ROM, strength-power and anthropometric characteristics in elite breaststroke swimmers and is the second known study to investigate the relationship between dryland strength-power and breaststroke kinematic parameters. Statistical analyses identified several strong relationships between dryland strength-power and kinematic parameters at 200 m, 100 m and maximal paces. These relationships partially supported hypotheses regarding the association between upper-body strength measures and propulsive pull, and lower body strength measures and propulsive kick. Findings from correlational analyses did not support the hypothesis that performance across a series of dryland strength-power measures would not strongly relate to passive and recovery phase kinematics in breaststroke swimming.

Assessment of the relationships between breaststroke kinematics and dryland strength-power parameters revealed a number of strong correlations with large effect. Strong relationships were most commonly seen between dryland strength-power and kinematic parameters at 100 m and maximal paces (n = 11) when compared to 200 m pace (n = 5). Strength and power capacities may consequently be of greater importance to performance across 100 m and 50 m distances. This suggestion is yet to be empirically explored however results from such an investigation would have significant implications on the design and delivery of strength and conditioning programs to elite breaststroke swimmers. The comparatively small number of dryland strength-power parameters found to be strongly related to kinematic parameters at 200 m pace suggests that other factors, including physiology or stroke efficiency, may have greater influence on performance across this distance.

The strength of relationships between SR, SL and dryland strength-power parameters varied according to athlete sex and swimming pace. Dissimilar to findings of Invernizzi et al. (2014), which reported a strong relationship between SR and pull up performance in both male and female athletes at 100 m pace, the present study established a strong relationship between pull up performance and SR in female athletes only. Extending on findings reported by Invernizzi et al. (2014), this relationship was also strong at 200 m and maximal paces in female athletes. Failure to identify a consistent relationship between SR and pull up performance in male and female athletes in the present study may be attributed to low subject numbers in the present study and a consequent reduction to statistical power. Inconsistency in the reported relationship between SR and pull up performance between studies may otherwise be attributed to the use of differing measures of upper-body capacity. The use of a maximal velocity pull up test, a power measure, in comparison to the exhaustive pull up test reported in Invernizzi et al. (2014), a muscular endurance measure, alters the upper-body capacity used to evaluate the relationship to SR. In response to the difference in capacity measures, it is suggested that an athlete's ability to continually overcome resistive forces is more closely related to SR in male swimmers than the rate of force development. Conversely both upper-body power and endurance appear to be strongly associated with SR in female breaststroke swimmers.

The strength and direction of relationships between SL and countermovement jump height also varied according to athlete sex and swimming pace. Strong relationships between SL and countermovement jump height were identified in male swimmers at 100 m and maximal paces. Higher SL was associated with greater countermovement jump height at both paces in males. Again, dissimilar to findings of Invernizzi et al. (2014), a similar relationship was not established within the female cohort in the present study. Variability in the strength of relationships between SL and countermovement jump height at various paces and between sexes may be due to the influence of other mediating factors, such as glide time, or an erroneous assumption regarding the relatedness of these two parameters. The link between SL and countermovement jump height is based on the assumption that SL is largely influenced by hip velocity throughout the kick propulsive phase, and the muscle groups used during countermovement jump performance are similar to those used in breaststroke kick (Invernizzi et al., 2014). Assessment of the relationship between hip velocity throughout the kick propulsive phase and SL within the present sample revealed only weak to moderate correlations except for males at 100 m pace ($r = -0.58$, <0.01 and -0.31 for females and -0.09, 0.74 and 0.62 for males respectively). The limited relatedness of hip velocity throughout the kick propulsive phase and SL indicates a direct relationship between SL and countermovement jump performance based on the above-described assumption is unlikely. In response to this finding, the mechanisms that underpin the relationship between countermovement jump and SL should be investigated in greater detail to better understand this relationship and determine how countermovement jump exercises can be prescribed to effectively influence SL in breaststroke swimmers.

In opposition to hypotheses that strength-power measures would not be strongly related to hip velocity throughout passive or recovery stroke phases, six strong correlational relationships between dryland measures and passive or recovery phases were identified (Tables 5.3 and 5.4). The reason for the strong association between these parameters is unclear. It is expected that the reported strength of these relationships would decrease in most cases with the use of a larger sample and instead indicate a weak association between dryland strength-power capacities and hip velocity throughout passive phases. The continued association of dryland strength-power parameters and passive stroke phases, with use of a larger sample, could be attributed to the occurrence of these phases directly after a propulsive phase and a consequent influence on the average hip velocity achieved during these phases.

Models of best fit explained between < 1% and 87% of variance between dryland strength-power measures and hip velocity throughout the propulsive phases. Models that explained a high amount of variance ($R^2 > 0.70$), can be used to provide an indicator of expected average hip velocity throughout propulsive phases. Whilst these models only represent preliminary findings due to low subject numbers, this type of analysis has potential application to be used for the assessment of hip velocity discrepancy between expected and achieved values. This type of assessment can subsequently act as a catalyst for the evaluation of technical proficiency. For example, the calculation of predicted hip velocity values more than of those reached when swimming may indicate the existence a technical error within the respective propulsive phase. The strength of listed models also supports the prescription of dryland strength and power training for the improvement of average hip velocity reached throughout propulsive pull and kick phases in elite breaststroke swimmers. Future research should seek to investigate the effect of dryland strength and power training on hip velocity throughout the propulsive phases via intervention to support this idea.

Despite providing preliminary evidence in support of the relationship between dryland strength-power parameters and breaststroke kinematics, results of the present study are limited by the sample size recruited for participation. Although statistical corrections were made through use of Hedges' g to avoid the underestimation of relationship strength, the use of a larger sample in future studies would add statistical power and aid in the generalisability of reported relationships to the wider population. It is also acknowledged that findings of the present study cannot be generalised to evaluate associations between dryland strength-power parameters and centre of mass velocity due to the assessment of hip velocity. Assessment of the hip as a fixed point on the body has previously been reported to overestimate velocity maxima and minima throughout the breaststroke cycle when compared to the centre of mass (Gourgoulis et al., 2018). Velocity values reported throughout the present study may consequently differ to those expected in report of the centre of mass, which may subsequently change the strength of reported associations between dryland strength-power parameters and breaststroke velocity. Future research studies should seek to investigate the associations between dryland strength-power parameters and centre of mass velocity to better understand how associations between hip and centre of mass velocity differ.

Future research studies should also seek to assess velocity patterns across time-trial or competition events rather than paced efforts to ensure the ecological validity of velocity patterns and the reported relationships between dryland strength-power parameters and breaststroke kinematics in elite breaststroke swimmers. The inclusion of additional ROM assessment sites specific to breaststroke swimming, including ankle external rotation with dorsiflexion, would also provide further insight into the characteristics of elite breaststroke swimmers and the role that ROM may have on breaststroke velocity.

5.6 Practical Applications.

Results of the present study have several practical applications to dryland training prescription and stroke evaluation. The frequent strong association of dryland strength-power parameters and stroke kinematics at 100 m and maximal paces should be considered by strength and conditioning coaches in the prescription of dryland training for sprint breaststroke swimmers. In response to reported findings coaches should consider the inclusion or continued prescription of explosive movements, such as the power-based measures described in the present study, in dryland training programs designed for sprint breaststroke swimmers. Results of the present study can also act as a catalyst to technique evaluation. The comparison of predicted hip velocity values calculated from the reported models of best fit and actual hip velocity values, provide coaches with a method of assessing propulsion effectiveness. Discrepancies between predicted and achieved values may indicate a stroke ineffectiveness throughout the respective propulsive phase and should promote technique evaluation in effort to maximise propulsive velocity.

5.7 Conclusion.

The frequency of strong relationships between dryland strength-power characteristics and stroke kinematics at 100 m and maximal paces highlights a need to include or continue the prescription of power-based activities in dryland programs designed for sprint breaststroke swimmers. Strong predictive equations modelling the relationship between phase velocities and dryland strength-power capacities provides a base from which current and predicted hip velocity can be compared. This information can be used to promote technique evaluation and suggests that strength and power training may be of benefit to elite breaststroke swimming performance.

Chapter Six: Three-Dimensional Video-Based Analysis in Aquatic Environments

6.1 Chapter Outline

The 3D video-based analysis methods described in this chapter further detail those outlined in Chapter Four. The chapter will initially provide an outline of the types of video-based analysis and the challenges faced when using these methods in an aquatic environment. The chapter will then discuss the analysis process in three sections: equipment acquisition and set-up, volume calibration and data collection. Within each section the specific methods used in "Hand, Knee and Foot Path Patterns in Elite Breaststroke Swimmers and their Association to Hip Velocity at 100 m Pace" (Chapter Four), will be detailed and their association to the existing literature or theory provided. All methods described in this chapter are based on the use of direct linear transformation (DLT) for the calibration and reconstruction of space using camera images.

6.2 Types of Video-Based Analysis

Video-based analysis methods are commonly used in sports science practice to analyse the execution of an athletic activity. These methods involve the video-recording of an athlete as they perform a skill or movement and a subsequent evaluation of athletic performance using the recorded footage. Simple application of video-based analysis methods may involve a coach filming an athlete while they perform a skill and replaying this video to the athlete for self-evaluation. More complex applications of video-based analysis involve the calculation and assessment of body segment and/or joint kinematics and the extraction of critical parameters. The number and type of parameters selected for assessment is dependent on the skill of interest. These parameters also determine the type of video-based method that should be used.

Video-based kinematic analysis can be conducted in two- or three-dimensions. Two-dimensional (2D) analysis requires the use of one camera and is used to assess skill performance along a single plane. Although 2D analysis can be simple (ie. minimal equipment, set-up, and processing requirements), it is limited to single plane movement. This makes it unsuitable for detailed analysis of many sporting tasks. For the analysis of multiplanar movements such as swimming, three-dimensional (3D) analysis is consequently preferred.

Three-dimensional video-based analysis is a data collection method that enables the quantitative evaluation of multiplanar movement through space. This method requires a minimum of two cameras for the computation of 3D position, and three non-colinear markers for the estimation of body pose. Commonly used in aquatic environments to assess the multiplanar movement of swimming, 3D video-based analysis has previously been used to evaluate stroke technique and efficiency (Silvatti et al., 2013).

6.2.1 Challenges of Using Video-Based Analysis Methods in Aquatic Environments

Three-dimensional video-based analysis has previously been used in both land-based and aquatic contexts. Although the underlying principles remain the same between media (ie. air and water), several characteristics of water make the use of videography more challenging in aquatic environments. One challenge specific to aquatic environments such as those in the present program, relates to difficulties in tracking fiduciary points on the body (commonly referred to as markers). Dissimilar to land-based videography, marker tracking is hindered by water turbulence, the presence of bubbles, insufficient lighting and the disappearance of markers due to movement between above and below water levels in aquatic environments (Kwon & Casebolt, 2006; Sanders, Gonjo, et al., 2015). Another issue specific to 3D video-based analysis in aquatic environments is light refraction. Typically, 3D video-based analysis in aquatic environments involves the placement of cameras behind underwater viewing windows or in underwater camera housings. This results in a density difference between contacting media (ie. water, glass and air) and causes light to refract in a non-linear manner (Kwon & Casebolt, 2006). The refraction of light in this manner results in image distortion, reducing the accuracy of kinematic parameter calculation unless corrected for (Kwon & Casebolt, 2006; Monnet et al., 2014).

6.3 Equipment Acquisition & Set Up

Three-dimensional video-based analysis is reliant on two pieces of equipment: video-recording cameras and a calibration structure or wand. The specifics of both cameras and the calibration structure used in Chapter Four were designed and selected in accordance with the requirements of DLT.

6.3.1 Cameras

6.3.1.1 Camera Number and Placement

Experimental set up in the present study consisted of nine stationary cameras (five below- and four above-water). This was comparable to previous studies of swimming kinematics, which have typically used six cameras in the experimental set up (two cameras above- and four cameras below-water level) (de Jesus et al., 2015; Figueiredo et al., 2011; Komar, Sanders, et al., 2014; Psycharakis et al., 2010; Psycharakis et al., 2005; Sanders, Gonjo, et al., 2015; Seifert, Komar, Crettenand, & Millet, 2014). The decision to use an additional underwater camera in the present study was based on the inclusion of camera views directly front-on and behind the direction of swimming. The inclusion of the additional camera in this context increased the likelihood that underwater body markers would be visible to at least two cameras at a given time, including one of the front-on or behind views. The visibility of body markers by a minimum of two cameras at a given time ensured the estimation of 3D coordinates using triangulation was possible. This reduced the number of instances at which joint locations required estimation, increasing analysis accuracy (Psycharakis et al., 2010). The inclusion of front-on and behind views also ensured that angles between cameras were within ranges previously accepted within the relevant literature (~41° and 110°) (Figueiredo et al., 2011; Gourgoulis et al., 2018).Three below-water cameras (cameras one, three and five) were mounted using a tri-suction cup mount. The remaining two below-water cameras (cameras two and four) were mounted using a wall bracket. All above-water cameras were mounted using free-standing tripods. Cameras were positioned according to the schematic provided in Figure 6.1 to provide a full view of the intended capture volume. Cameras were also positioned at various depths to avoid errors associated with camera axes being on the same plane as the reference frame (Psycharakis et al., 2005).

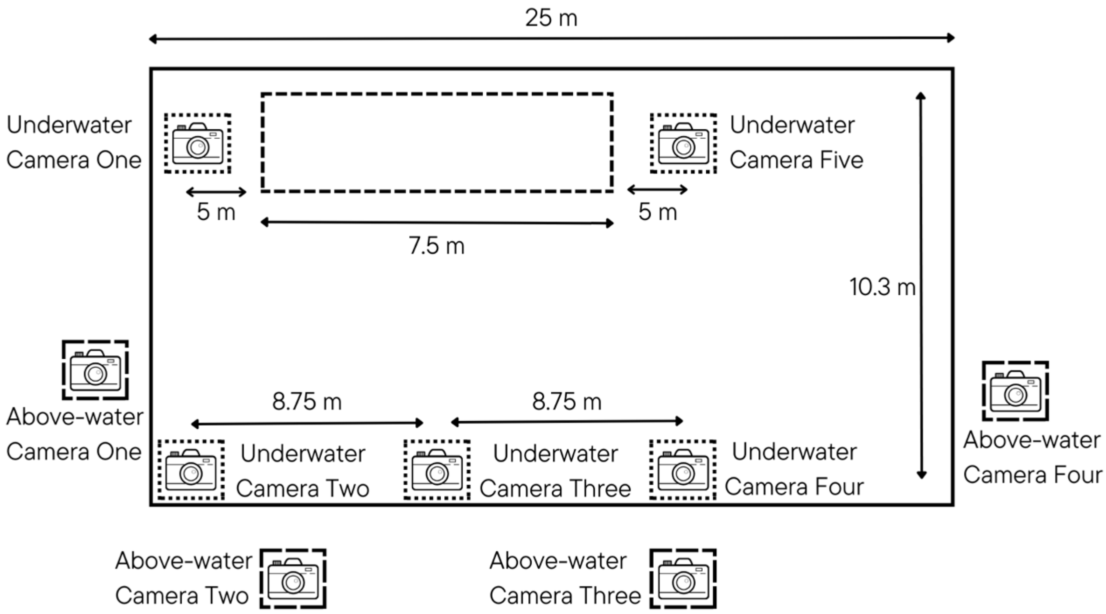

Figure 6.1 Pool Calibration Set Up and Camera Placement Schematic.

6.3.1.2 Underwater Camera Properties

Five underwater Barlus UW-S2Z-C6X25 cameras (Shenzhen Zhiyong Industry Co, China) were used in the present study. Cameras were fitted with a fish-eye lens and an adjustable focal length of 2.8 – 12 mm. To account for image distortion that results from use of a fish-eye lens (Payton & Hudson, 2017), video images were corrected using a proprietary software prior to analysis (Figure 6.2). Focal length of cameras one, two, three and four were set at 2.8mm. The focal length of camera five was adjusted to include only the intended calibration volume and a small area around the calibration structure within the field view. Additional space around the intended capture volume was provided to accommodate for image correction. Shutter speed was automatically selected and adjusted by each camera after visual inspection of output images were considered of an acceptable brightness. The final camera property adjusted prior to study commencement was frame rate. All cameras captured footage at 50Hz to ensure instances of maximum and minimum displacement, and the beginning and end of temporal phases were accurately captured (Payton & Hudson, 2017). This frame rate has previously been used for the kinematic investigation of freestyle and breaststroke swimming (Komar, Sanders, et al., 2014; Psycharakis et al., 2010; Sanders, Gonjo, et al., 2015; Seifert, Komar, Crettenand, & Millet, 2014).

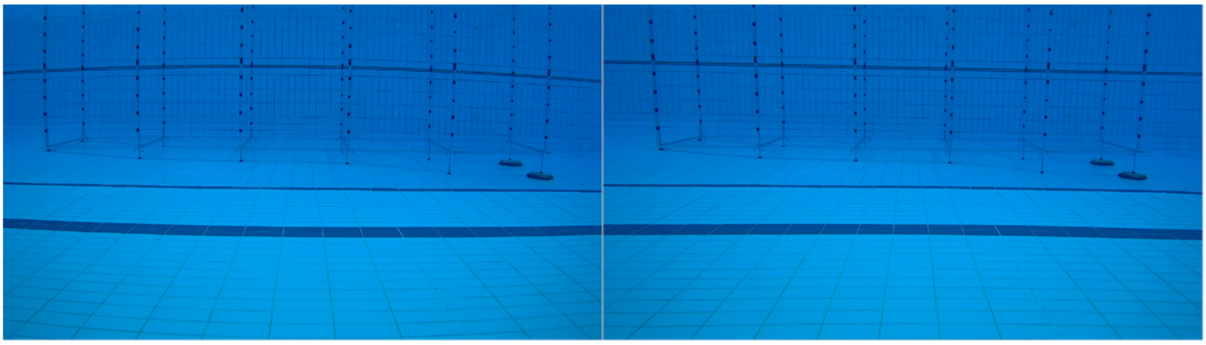

Figure 6.2 Images of the Calibration Structure Before and After Image Correction.

6.3.2 Calibration Structure

Two methods are typically used to calibrate an intended capture volume: static calibration structures and dynamic wand/chessboard methods. The use of a static calibration structure was selected for use in the present study based on previous use within similar research environments.

6.3.2.1 Structure

The calibration structure used in the present study was custom-built for use in the testing pool. The structure was designed and engineered by Change Parts Pty Ltd (Hallam, Victoria). Frame structure was designed with consideration of breaststroke cycle length, depth, width, and the existence of an uneven pool floor gradient. Adjustable feet were included in the final design to accommodate for this floor gradient and ensure horizontal beams of the structure remained parallel to water-level. The structure consisted of five 1.5 x 1.5 x 1.8 m sections, totalling a 7.5 x 1.5 x 1.8 m space along the *x*, *y* and *z* axes respectively prior to height adjustment. Each section was constructed using 32mm square aluminium tubing. The same tubing was used to connect adjacent sections, which were subsequently fastened using D clip lynch pins to ensure structure rigidity. The structure used within the present study had a longer *x* axis than previously reported calibration structures: 4.5 x 1.5 x 1 m (Komar, Sanders, et al., 2014; Psycharakis et al., 2010; Psycharakis et al., 2005; Sanders, Fairweather, et al., 2015; Sanders, Gonjo, et al., 2015), 6 x 2.5 x 2 m (de Jesus et al., 2015; Sanders, Gonjo, et al., 2015), 6 x 3 x 2 m (Seifert, Komar, Crettenand, & Millet, 2014) and 3 x 2 x 3 m (Figueiredo et al., 2011). This decision was made based on previous report that breaststroke stroke length can reach up to 2.22 m in competition

(Thompson et al., 2000). The use of a 7.5 m long structure consequently ensured that a minimum of two full stroke cycles were captured within the intended capture volume.

6.3.2.2 Control Points

In order to calculate the 11 DLT coefficients described in section 6.4.2, a minimum of six control points of known location within the real-world frame of reference are required (Challis & Kerwin, 1992). A total of 48 above-water and 60 below-water control points were marked at 0.25 m intervals along the vertical axes of the frame using black cloth tape in the present study. The decision to include additional control points was made in response to findings of Chen et al. (1994) that found the inclusion of additional control points increased the accuracy of 3D reconstruction. The number of control points used in the present study was equivalent to the optimal number of control points per cubic metre reported by Chen et al. (1994). Control points were evenly distributed within the intended calibration volume to further improve calibration accuracy (Chen et al., 1994; Kwon & Casebolt, 2006)

6.4 Volume Calibration

6.4.1 Introduction to DLT

DLT is the most widely used 3D reconstruction algorithm for motion analysis in aquatic environments (Kwon & Casebolt, 2006; Payton & Hudson, 2017), and is used to determine the linear relationship between pixel coordinates on a 2D image and 3D coordinates within the real-world frame of reference (Payton & Hudson, 2017). Based on the collinearity condition, the DLT algorithm assumes that that the position of an object in space and the position of that image point on an image plane are related (Kwon & Casebolt, 2006).

The linear relationship between a point on a 2D image and its corresponding 3D coordinate can be described using Equations 6.1 and 6.2 (Abdel-Aziz et al., 2015)

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1} \quad (6.1)$$

$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \quad (6.2)$$

where *x, y, z* are the coordinates of a given point within the real-world frame of reference, *u* and *v* are the image coordinates of the same points and L_1 to L_{11} are the DLT coefficients that represent internal parameters and orientation of the camera (Abdel-Aziz et al., 2015; Chen et al., 1994; Kwon & Casebolt, 2006).

In its standard form, DLT does not include parameters that account for optical distortion (Silvatti et al., 2013). Hatze (1988) modified the original approach to account for optical distortion parameters however the modified method did not account for additional non-linear distortions that occur in aquatic environments due to the refractive interaction between the water and camera lens (Silvatti et al., 2013). The modified approach was consequently not used for analysis in the present program.

6.4.2 Calibration Process

The volume calibration process required of DLT is used to calculate the 11 DLT coefficients stated in equations 6.1 and 6.2. This process is completed through the mapping or matching of known coordinates within the real-world frame of reference to their corresponding pixel coordinates from various camera images. Static images of the calibration frame positioned at the intended testing site were captured from each of the nine camera views prior to test commencement. Control points positioned on the calibration frame were subsequently digitised on a proprietary software, Cinalysis, in order to obtain the *u,v* coordinates of each control point. Matching the pixel coordinates of control points to their known 3D coordinates within the real-world frame of references, the 11 intrinsic (focal length, distortion parameters, principal points, pixel scale factor) and extrinsic (location and orientation) DLT coefficients were then calculated using Equation 6.3 (Silvatti et al., 2012). This process was completed separately for each camera view.

At the time of image capture no additional structures or persons were in the water to minimise water disturbance and maximise calibration accuracy. The calibration structure was then disassembled and removed from the testing space for the duration of testing.

$$\begin{bmatrix} x & y & z & 1 & 0 & 0 & 0 & 0 & -ux & -uy & -uz \\ 0 & 0 & 0 & 0 & x & y & z & 1 & -vx & -vy & -vz \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \\ L_7 \\ L_8 \\ L_9 \\ L_{10} \\ L_{11} \end{bmatrix} = \begin{bmatrix} u \\ v \end{bmatrix} \quad (6.3)$$

6.4.2.1 Image Correction

As described in Section 6.3.1.2 the cameras used in the present study produced images with a fish-eye appearance. If used to obtain pixel coordinates for use in the DLT algorithm this would have resulted in geometric measurement inaccuracy. Image distortion was consequently corrected prior to calibration following methods similar to those described by Wu et al. (2013). Correction was conducted using a planar checkerboard grid with 30 mm squares. Prior to test commencement a video was collected of the checkerboard moving through each camera field of view. This video was subsequently imported into the Cinalysis software and used to obtain 51 static images. Using these images the software subsequently calculated the level of image distortion and provided an image correction file to remove the appearance of fish-eye. This file was then applied to all videos of these same camera view prior to calibration and marker tracking. Figure 6.2 provides a comparison of images before and after image correction.

6.4.3 Reconstruction

The second process completed using DLT is reconstruction. This involves the calculation of 3D coordinates within the real-world frame of reference using known pixel coordinates (*u, v*) and the internal parameters of cameras within the experimental set up ($L_1 – L_{11}$).

Equation 6.4 is used to solve for *x*, *y* and *z* coordinates at a single point using known pixel coordinates and DLT coefficients calculated during calibration (Kwon & Casebolt, 2006). This equation can be used to calculate any 3D position within the intended calibration volume, however the accuracy of reconstruction significantly reduces for any point located outside of the calibration volume (Psycharakis et al., 2010; Wood & Marshall, 1986).

$$\begin{bmatrix} L_1 - uL_9 & L_2 - uL_{10} & L_3 - uL_{11} \\ L_5 - vL_9 & L_6 - vL_{10} & L_7 - vL_{11} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u - L_4 \\ v - L_8 \end{bmatrix} \quad (6.4)$$

6.4.3.1 Reconstruction Error

The accuracy of 3D reconstruction is assessed using reconstruction error. This involves the comparison of 3D coordinates within the real-world frame of reference to reconstructed 3D coordinates of the same points. Reconstruction error of a single point is calculated using Equation 6.5 and total reconstruction accuracy is calculated using Equation 6.6 (Kwon & Casebolt, 2006).

$$\varepsilon_i = \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2 + (z_i - \hat{z}_i)^2} \quad (6.5)$$

$$\varepsilon_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \varepsilon_i^2} \quad (6.6)$$

where x_i, y_i and z_i are coordinates within the real-world frame of reference, $\hat{x}_i, \hat{y}_i$ and $\hat{z}_i$ are the reconstructed coordinates, and ε_{RMS} is the root mean square error computed from summed squared errors ε_i of n data points in the i^{th} instances.

Reconstruction in the present study was separated into above- and below- water volumes. The above-water volume was defined as all space above waterline (*z*-axis markers ≥ 0). The below-water volume was defined as all space below waterline (*z*-axis markers ≤ 0). Reconstruction error is typically higher on the horizontal axis when compared to other axes (Figueiredo et al., 2011). Error is also higher in below-water volumes when compared to above-water volumes due to non-linear light refraction and a resultant image distortion (de Jesus et al., 2015; Figueiredo et al., 2011; Kwon & Casebolt, 2006).

Reconstruction errors of 3.9 mm *x*, 3.8 mm *y*, 4.8 mm *z* (Psycharakis et al., 2005), 0.1% *x*, 0.2% *y*, 0.1% *z* of calibrated space (Psycharakis et al., 2010) and 1.8 mm *x*, 1.92 mm *y*, 6.1 mm *z* (Chen et al., 1994) for below-water volumes have previously been reported within the literature. Reconstruction errors of 1 mm *x*, 2 mm *y* and 0 mm *z* were calculated for the below-water volume in the present study. These levels of reconstruction error are considered acceptable for 3D video-based kinematic analysis in swimming (Figueiredo et al., 2011).

6.5 Data Collection

6.5.1 Marker Placement

Nine anatomical markers were used in the present study: centre of head, humerus greater tubercule, olecranon, ulnar styloid process, third finger distal phalanx, iliac crest, femur lateral epicondyle, lateral malleolus and first distal phalanx of the hallux. Marker placement was selected to closely match body landmarks previously reported in similar studies (Komar, Herault, et al., 2014; Psycharakis et al., 2010; Sanders, Gonjo, et al., 2015; Seifert, Komar, Barbosa, et al., 2014). Dissimilar to several exisitng studies, markers were only placed on the left side of the body in the present program as all cameras were positioned along one side of the pool. Swimmers were consequently instructed to swim in one direction only to ensure body markers were visible from each camera view. Anatomical landmarks of the humerus greater tubercule, olecranon, ulnar styloid process, iliac crest, femur lateral epicondyle and lateral malleolus were marked with a waterproof light-emitting diode (LED) and affixed with Tensospray® and sports strapping tape to ensure they remained in place (Figure 6.3). Anatomical landmarks at the centre of the head, third finger distal phalanx and first distal phalanx of the hallux were marked with black cloth tape only.

Figure 6.3 Example LED Light Affixation.

6.5.2 Synchronisation Light

Cameras used within the present study could not be genlocked. A pair on manually triggerable synchronised LEDs were consequently placed within view of all cameras during testing and triggered at the commencement of each trial. The first frame in which one LED was visible from each camera view was subsequently used to synchronise footage from all cameras during post-processing.

6.6 Summary

Three-dimensional video-based methods are the current gold standard for multiplanar analysis in aquatic environments. To ensure the reliability of data acquired using these methods, several considerations about equipment selection and set-up are required. These include camera number and position, camera properties, calibration structure design, control point position and body marker placement. Compliance with these methodological requirements ensures that DLT can be used to accurately reconstruct 3D coordinates within the real-world frame of references using 2D pixel coordinates from camera images.

The synthesis of theory underpinning 3D video-based analysis methods and its application in aquatic environments helps to position the current research program amongst similar research investigations. The synthesis of information throughout this chapter also justifies the methodology reported in Chapter Four. Collating the existing theoretical and applied knowledge in this way, information provided in this chapter can be used as reference in the development of research investigations considering the use of 3D video-based methods in future.

Chapter Seven: Thesis Summary

7.1 Introduction

Maximising swimming speed in breaststroke competition is in part reliant on an understanding of how biomechanical parameters influence average velocity across the stroke cycle. Following a review of the literature in Chapter Two, it was established that much of the existing research investigating breaststroke biomechanics in elite populations had reported the temporal and neuromuscular activity characteristics of this population. Scope to conduct additional investigation into biomechanical parameters that have not been extensively examined within the existing literature was consequently identified and used to inform the present body of research. Further investigation into these parameters was conducted with intent to provide coaches, swimmers and applied sports practitioners with greater understanding of the biomechanical considerations relevant to the development of training programs tailored for elite breaststroke swimmers. More specifically, this thesis aimed to evaluate the relationship of temporal characteristics, hand, knee and foot path patterns, and physical attributes to breaststroke performance within elite populations.

The purpose of this final chapter is to consolidate findings of each of the three original research investigations that comprise the present research program. Throughout this chapter applications of key findings to the training and competition environment will also be presented. The chapter will subsequently provide suggestions for future research investigation and discuss the limitations of methods used throughout the body of research.

7.2 Main Findings

Findings of this thesis demonstrated the existence of group-based temporal pattern differences and established the associations of temporal characteristics, body segment path patterns and dryland strength-power attributes to breaststroke hip velocity. Together these findings highlighted a need for coaches and applied sports practitioners to consider event-specific demands, athlete sex, path patterns of the hand, knee and foot, and strength-power attributes of a swimmer in the design of training programs for the improvement of breaststroke competition performance.

Regarding event-specific considerations, investigation of the temporal patterns used in elite breaststroke competition revealed characteristic temporal differences between-groups based on race distance and athlete sex. Comparison of temporal patterns used during 100 m and 200 m competition evidenced a coupling of reduced time spent in passive phases (pull delay, passive kick and glide) with increased time spent in propulsive phases (propulsive pull and propulsive kick) throughout the stroke cycle when swimming the 100 m event. This indicated that swimmers elected to minimise passive phases associated with deceleration and maximise movement phases associated with acceleration when swimming the 100 m to maintain a higher average velocity during this event.

Comparison of the temporal patterns used by male and female athletes at the same race distance also highlighted characteristic temporal pattern differences. At both 100 m and 200 m distances, male athletes typically spent a greater percentage of stroke time in propulsive phases and a lower percentage of stroke time in passive and recovery phases when compared to female athletes. Sex-based temporal differences were attributed to typical morphological differences between males and females. Specifically, the increased size and larger propelling surface area typically exhibited by male swimmers was thought to explain the increased time male athletes spent in propulsive phases. An increased amount of adipose tissue typical to female morphology and a consequent reduction to energy cost required to maintain an efficient glide position was instead used to explain the increased amount of time female athletes elected to spend in the glide phase (Seifert & Chollet, 2005). Collectively findings of Chapter Three demonstrated a need for coaches to consider the event-specific demands and morphological characteristics of an individual in the design and delivery of training programs that involve the modification of temporal patterns for the improvement of competition performance.

An additional outcome of significance from Chapter Three was the development of a reliable method of temporal pattern assessment in competition. Improving on the ecological validity of previous temporal pattern investigation, which has previously been conducted using 25 m paced efforts, the development of this competition-specific method enabled the assessment of 15 temporal phases using a single standing camera. The breaststroke phase model subsequently designed for use with this analysis method informed the definition of temporal phases throughout Chapters Four and Five. Studies detailed within these chapters specifically investigated the biomechanical parameters that effect average hip velocity achieved throughout the propulsive pull phase, propulsive kick phase and the total stroke cycle.

Velocity maintenance of the hip throughout the breaststroke propulsive phases was reported to be associated with path patterns of the hand, knee and foot in elite breaststroke swimmers. Specifically, associations between hand path and hip velocity characteristics indicated that swimmers who achieved higher average hip velocity across the total stroke cycle typically had greater total hand displacement during the insweep phase, achieved relative vertical alignment in the lateral axis of the hip, knee and foot at the beginning of the propulsive kick phase and the subsequently followed a short foot path throughout the remainder of this phase. From associations between hand, knee and foot path patterns it was also reported that swimmers who reached a greater maximal position of the hand along the lateral axis and did so following a direct hand path during the outsweep phase, maintained higher average hip velocity across the subsequent insweep phase. The outsweep phase was consequently considered important in the set-up of an insweep phase that could follow a large total hand path. This would then result in the achievement of higher average hip velocity across the total stroke cycle.

Another performance variable found to influence hip velocity throughout the breaststroke propulsive phases of elite swimmers was the dryland strength-power attributes of individual athletes. Most frequently observed at 100 m and maximal paces, strong positive associations ($r > 0.70$) between mean chin up velocity, countermovement jump height and hip velocity throughout the propulsive phases indicated that swimmers who performed better on these dryland measures achieved higher average hip velocity during both propulsive pull and propulsive kick phases. The strong association of dryland strength-power parameters to hip velocity throughout the propulsive phases in breaststroke swimming provided preliminary evidence to support the translation of dryland physical characteristics to swimming kinematics. Collectively findings of Chapters Four and Five indicated that elite breaststroke swimmers who followed body segment paths that allowed for a large hand path during the insweep phase, achieved relative lateral proximity of hip, knee and foot segments at the beginning of the propulsive kick phase and followed a short foot path during the subsequent propulsive kick phase maintained higher average hip velocity across the total stroke cycle. To enable the translation of reported technical solutions to the improvement of average swimming velocity, swimmers were also required to possess high levels of dryland strength-power. In application of these findings to the training environment, it is hoped that the optimisation of body segment path patterns and dryland strength-power attributes of elite breaststroke swimmers can improve elite breaststroke swimming performance.

7.3 Methodological Implications

This research program made several methodological contributions to the existing research space. Contributions included the development of a valid and reliable method of automatic marker tracking and a novel method of temporal analysis that enabled the assessment of temporal characteristics using competition footage. Together these contributions aided in the generation of knowledge about elite breaststroke swimming populations that was not previously available and will reduce the processing resources required to conduct related research in the future.

7.3.1 Automatic Marker Tracking

One of the barriers that has historically deterred researchers from conducting 3D video-based analysis in aquatic environments is the associated time requirement (Sanders, Gonjo, et al., 2015; Silvatti et al., 2013). Traditionally, researchers have been required to manually track body landmarks of interest. This process is both time consuming and at times subject to analyser error due to the presence of bubbles or white water (Monnet et al., 2014; Sanders, Gonjo, et al., 2015; Silvatti et al., 2013). Coinciding with technology development over the past decade is an increased availability of artificial intelligence and computer vision. One of the specific capabilities of these computer-based algorithms with potential application to sports science research is pose estimation, which refers to the estimation or inference of joint locations and body segments using still images or videos (Desmarais et al., 2021). The application of pose estimation software has been observed across a multitude of sporting contexts, however its use in aquatic environments has only been trialled on one known occasion (Papic, Andersen, et al., 2021).

The feasibility of applying pose estimation technology to automatically track body landmarks in aquatic environments was assessed throughout data collection and analysis stages of the original research study detailed in Chapter Four. Using a freely available pose estimation software, Deep Lab Cut (Mathis Laboratory, Geneva, Switzerland), a series of pose estimation models were developed and subsequently evaluated against manually digitised points to assess model accuracy. Resulting from this evaluation process was a series of pose estimation models able to accurately track seven body landmarks (finger, wrist, elbow, hip, knee, ankle, toe) during breaststroke swimming from three different camera angles (two positioned at ~45° and one positioned perpendicularly to the direction of swimming).

The use of pose estimation models significantly reduced the amount of time required to process and track body landmarks in the present research program when compared to report of previous research groups utilising manual digitisation methods. In addition, it limited analyst error that is frequently associated with manual digitising. The established validity of aquatic-based pose estimation models in the present research program should give researchers greater confidence in its applicability in both research and applied contexts. Following methodological processes outlined in Chapter Four, researchers can continue to use pose estimation to reduce processing requirements traditionally associated with 3D video-based analysis, increasing the accessibility of 3D kinematic analysis in future.

7.3.2 Temporal Pattern Analysis

Competition outcomes are typically considered the primary measure used to evaluate swimming performance. Previous temporal pattern analysis however, has been restricted to 25 m paced efforts. The consequent reduction to ecological validity was identified as a limitation of the existing literature within Chapter Two. To address this limitation and assess the similarity of temporal patterns used in paced and competition efforts, a novel method of analysis was developed as part of the original research investigation detailed in Chapter Three. Developed as an adaptation of the breaststroke phase-model reported by Chollet et al. (2004), this method involved the identification of six time points or movements within the stroke cycle using footage collected from a single standing camera positioned at 25 m along the length of the pool and approximately 10–20 m above water level. Using these six points, 15 temporal phases were subsequently calculated following procedures detailed in Chapter Three. Demonstrated to hold high reliability using ICC, this method provides research groups and applied sports practitioners with the ability to accurately assess temporal patterns in competition. The method is also advantageous due to minimal set up requirements and the use of footage that is already frequently collected in the competition environment. The use of data collection methods considered minimally intrusive to the competition environment, an environment that is traditionally strictly regulated, makes this method accessible at various levels of competition. This enables coaches and performance practitioners to obtain additional information regarding competition kinematics and use this information to evaluate breaststroke swimming performance.

7.4 Practical Applications

Findings of this thesis have several applications to the training and competition environment. Of relevance to elite breaststroke swimming coaches, technical solutions presented throughout this research program can be used to inform those prescribed to swimmers. Findings presented in this thesis demonstrated that elite breaststroke swimmers elected to minimise the amount of time spent in temporal phases associated with deceleration and maximise the amount of time spent in temporal phases associated with acceleration during 100 m competition to maintain a higher average hip velocity during this event when compared to the 200 m event. In the prescription of training programs for sprint breaststroke swimmers, coaches should consequently work with swimmers to maximise the amount of time spent in propulsive phases and minimise the time spent in recovery and passive phases. This may be done by beginning the subsequent lateral hand movement earlier after kick completion and activating bicep femoris earlier in the kick recovery phase (Olstad, Zinner, et al., 2017). Velocity achieved during these propulsive phases and the total stroke cycle at 100 m pace can be optimised by following a large hand path during the insweep phase, achieving relative vertical alignment in the lateral axis of the hip, knee and foot at the start of the propulsive kick phase and following a short foot path throughout the remainder of this phase. Finally, athletes who achieved higher average hip velocity across propulsive pull and propulsive kick phases typically had greater mean chin up velocity and higher countermovement jump height. It should be noted that this association does not clarify whether individual strength-power characteristics mediate the execution of these technical elements, or are an attribute that can be further developed to increase velocity achieved throughout propulsive pull and propulsive kick phases. Findings of Chapter Five do however, support a requirement for elite breaststroke swimmers to have sufficient dryland strength-power capacities to support sprint breaststroke performance. In following the above-mentioned technical prescriptions, coaches can better tailor training programs for sprint breaststroke swimmers to improve elite breaststroke competition performance.

Modelled relationships between mean chin up velocity, countermovement jump height and hip velocity throughout the propulsive phases of breaststroke swimming (Chapter Five) can also be applied in the training environment to assess technical proficiency. Using modelled relationships provided in Chapter Five coaches can compare the expected and achieved propulsive hip velocity values of an individual, given an athlete’s performance across a chin up or countermovement jump measure. From this comparison coaches can subsequently make informed decisions regarding areas of individual performance improvement. If modelled or predicted hip velocity exceeded the hip velocity achieved by an athlete at a given pace, coaches could consider an evaluation of the individual’s technical proficiency throughout this propulsive phase to explain the reported discrepancy. With consideration of an identified technical inefficiency, coaches could subsequently develop a training intervention to address the inefficiency and over time increase hip velocity achieved throughout this propulsive phase. Attainment of hip velocity values greater than those predicted by the provided models could instead suggest that the individual is technically proficient throughout this phase. In such case coaches could work with their performance support team to increase the dryland strength-power attributes of the individual in effort to increase hip velocity throughout the propulsive phases.

7.5 Limitations

Whilst the development of a novel method for the assessment and analysis of breaststroke temporal patterns in competition improved the ecological validity of previously reported temporal information, several limitations of the analysis method detailed in Chapter Three must be acknowledged. The use of a single camera positioned 10 – 20 m above water level made the identification of several stroke points difficult, specifically the beginning of kick recovery and finish of propulsive kick. Whilst reliability of the method was assessed and the method considered reliable, future researchers using this analysis method should first assess the inter- and intra-rater reliability of results before drawing conclusions regarding breaststroke temporal patterns. Researchers may also consider the use of underwater vision when available to reduce the hinderance of water turbulence on vision quality.

It is also acknowledged that the analysis of temporal patterns in isolation of other contextual factors oversimplifies the complexity of elite breaststroke swimming performance. This was evidenced by the limited amount of variance explained by each of the four regression models developed to explain the relationship between various temporal parameters and overall race time (Chapter Three). Considering the influence of physiological, psychological and additional biomechanical factors would have enhanced the predictive ability of the regression models and increased the certainty with which conclusions about the influence of temporal patterns on elite breaststroke swimming performance could be drawn. This would consequently provide further assurance that the manipulation of temporal patterns in the training and competition environment can be used to improve athletic performance.

Addressing one of the identified shortcomings of Chapter Three, the inclusion of underwater cameras in the testing protocol outlined in Chapter Four reduced the hinderance of water turbulence on the identification of temporal phases throughout the stroke cycle. The inclusion of underwater cameras in this study also allowed for the assessment of outsweep and insweep phases, which was not possible from the single, above-water camera view outlined in Chapter Three. Although several characteristics of the testing protocol detailed in Chapter Four increased the accuracy at which temporal phases could be calculated, several limitations remained. The assumption of movement synchronicity between left and right sides of the body was one such limitation. Due to space constraints associated with the testing pool cameras could not be positioned on both sides of the testing space to allow adequate view of participants as they moved through the intended calibration volume. Cameras were consequently positioned on one side of the testing pool and body landmarks were only marked on the left side of the body. The resultant assumption of movement synchronicity and symmetry negates the potential influence of movement asymmetry on velocity characteristics in elite breaststroke swimming. The existence of displacement asymmetries in an elite breaststroke swimmer have previously been reported (Sanders, Fairweather, et al., 2015), however the effect of such asymmetries on average velocity remains unknown. Future research investigation into the influence of technique asymmetry on velocity in breaststroke swimming would aid to resolve this potential limitation of the present research program.

An additional limitation of the present program common to studies detailed in Chapters Four and Five relates to the availability of a small sample (n = 11). Whilst effort was made throughout the present program to statistically correct for the small sample size through use of Hedges' g estimate for effect size, it is acknowledged that small sample use is associated with increased susceptibility to Type I errors. The authors consequently made cognisant effort to avoid overstating the application of findings of studies detailed in Chapters Four and Five. Further investigation into the associations between hand, knee and foot path patterns, dryland strength-power and swimming velocity using a larger sample, or a sample consisting of different elite level breaststroke swimmers would greatly aid in supporting findings of the present program and increase the confidence with which reported conclusions could be generalised to the broader elite breaststroke population.

7.6 Future Directions

Findings of the present research program have extended on existing understanding of the temporal characteristics, path patterns of the hand, knee and foot, and physical attributes in elite breaststroke swimming. In addition to extending on the existing knowledge, reported findings have several applications to the training environment and improve on previous methodologies available for use in aquatic environments. To further extend on findings presented throughout this thesis several future research directions were identified.

The integration of muscle activation patterns, intra-cyclic velocity variations and pacing characteristics would be of benefit to future analysis of temporal patterns used in competition. The addition of these performance parameters would provide further contextual information to how temporal patterns vary within a race and why temporal patterns vary between individuals in the same race. Building on the methodological rigour of the competition-based temporal analysis method developed throughout the present program, future investigation could also consider the use of an underwater camera to enable the accurate assessment of additional temporal parameters including outsweep and insweep phases described by Chollet et al. (2004), Conceição et al. (2019), Leblanc et al. (2005) and Seifert and Chollet (2005).

To further extend on reported associations between path patterns of the hand, knee and foot and hip velocity in elite breaststroke swimmers, future research could investigate how similar displacement characteristics influence average velocity at maximal and 200 m paces. Given the described differences in temporal characteristics and strength associations between 100 m and 200 m paces throughout the present program, it was not considered appropriate to generalise reported associations from Chapter Four for application at other paces. Further investigation in this area would help to determine the event-specific considerations that should be made during the prescription of technique changes in elite breaststroke populations.

Given preliminary finding of strong cross-sectional relationships between dryland strength-power and hip velocity throughout the breaststroke propulsive phases in elite swimmers in the present program, future research groups should also seek to complete similar analysis utilising a larger sample or a longitudinal study design. This would provide additional strength to reported findings and increase the confidence with which findings could be generalised to breaststroke populations. The strength of reported relationships would again be enhanced through the exploration of dryland training interventions aimed at increasing average velocity during both propulsive pull and propulsive kick phases.

7.7 General Conclusions

This thesis aimed to evaluate the relationship of temporal characteristics, path patterns of the hand, knee and foot and physical attributes to breaststroke performance in an elite population. Identified as areas of underrepresentation within the existing literature the present program intended to extend on the knowledge base from which coaches, athletes and applied practitioners could make informed decisions about technical prescription in elite breaststroke populations.

Analysis of the temporal characteristics utilised by elite breaststroke swimmers within the present program provided first insight into how athletes coordinate movements of the upper and lower limbs during competition. Temporal patterns varied between 100 m and 200 m events, with patterns utilised in the 100 m event characterised by larger percentages of stroke time spent in propulsive phases, and reduced percentages of time spent in recovery and passive phases when compared to the 200 m event (Chapter Three). These differences highlighted a need to tailor technical interventions to meet event-specific requirements.

Additional context to the temporal phase models described in Chapter Three was provided through the evaluation of associations between path patterns of the hand, knee and foot and swimming velocity (Chapter Four). Throughout this chapter the displacement characteristics, specifically total 3D displacement, maximal lateral position and relative lateral position of the hand, knee and foot were estimated across propulsive phases and used to evaluate their association to hip velocity across the stroke cycle. Displacement characteristics were found to be associated with hip velocity in elite populations, with total hand displacement throughout the insweep phase, relative lateral position of the hip, knee and foot at the beginning of the propulsive kick phase and total foot displacement reported as the strongest associates to average hip velocity across the total stroke cycle. Hand displacement characteristics during the outsweep phase were also considered important in the set-up of the potential hand path travelled during the subsequent insweep phase.

Chapter Five detailed the associations between strength-power parameters and breaststroke swimming velocity. Strong associations ($r > 0.70$) between average chin up velocity, countermovement jump height and hip velocity throughout the propulsive phases were frequent at maximal and 100 m paces. These associations consistently indicated that athletes who performed better on dryland strength-power measures were able to achieve higher average hip velocity during both propulsive pull and kick phases. The frequency of such associations also provided preliminary evidence to the existence of a dryland strength-power component that mediates hip velocity in elite breaststroke swimmers at these paces.

The series of original studies presented in this thesis provided an additional knowledge base from which coaches, athletes and applied practitioners can draw upon to inform training and competition design specific to elite breaststroke swimming. Throughout this thesis the need to tailor training design to suit event-, sex- and individual-specific attributes has been demonstrated and findings of the present program further evidence the complex interplay of temporal characteristics, path patterns of the hand, knee and foot and physical attributes on swimming velocity in elite breaststroke swimming.

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