Effect of Central Motor and Neuromuscular Impairment on Freestyle Swimming Technique and Performance

Y LEE

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YU-HSIEN LEE

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Academic Outputs

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Abstract

Evidence-based classification is required in Para swimming to ensure athletes are not disadvantaged when competing against others in their allocated class, but there is a dearth of research on how central motor and neuromuscular impairment (CMNI) impacts a swimmer’s movement in the water. CMNI encompasses brain injury, spinal cord injury, as well as other neuromuscular disorders which affect the ability to coordinate movement. This thesis aimed to improve understanding of how CMNI influences freestyle swimming technique and the impact it has on performance. In study 1, analysis of 223 race performances showed stroke length rather than stroke frequency was the main factor limiting CMNI freestyle performance. In studies 2–5, three-dimensional motion analysis was utilised to establish freestyle biomechanical characteristics of highly trained CMNI (30) and non-disabled (13) swimmers. Study 2 examined upper limb, lower limb and trunk kinematics in front crawl; study 3 investigated body roll kinematics; study 4 determined intra-cyclic speed fluctuation, Index of Coordination and Froude efficiency. The final study focused on the kinematics of double-arm backstroke, a specialist freestyle technique. Compared to the non-disabled group, CMNI swimmers displayed irregular hand and wrist positions, shallow and short hand trajectories, restricted elbow and shoulder range of motion, atypical body roll profiles, affected function of upper and lower limbs, and less horizontally aligned body orientations. More impaired swimmers exhibited higher body inclination angles, greater intra-cyclic speed fluctuation and lower swimming speed, stroke length and Froude efficiency than less impaired swimmers. These results indirectly highlight the impact of impaired active range of motion, poor coordination and affected strength on CMNI freestyle kinematics and indicate that CMNI swimmer performance is likely limited by a reduced ability to generate propulsion, minimise drag and swim economically. A high heterogeneity existed in their activity limitations due to the nature of CMNI comprised of various type and severity. This thesis has contributed to knowledge of the biomechanical determinants of CMNI freestyle and thus may inform the development of a more evidence-based Para swimming classification system.

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Glossary of Terms

Term	Definition
Kinematics	The study of motion, describing how objects move without considering the forces involved.
Freestyle swimming	A race category in competitive swimming that allows swimmers to use any stroke technique they prefer. Front crawl is the most common technique used in freestyle events.
Front crawl swimming	A technique involving alternating cyclic movements of the upper limbs to propel the body through the water accompanied by alternating vertical movements of the lower limbs.
Stroke cycle	A complete cycle of the upper limbs from one hand entry to the water to the next same hand entry.
Propulsion	The hydrodynamic force acting on the swimmer in the direction of travel, produced by the swimmer's upper and lower limb actions in the water.
Active drag	The hydrodynamic, resistive force experienced by the swimmer opposite to their direction of travel, whilst actively swimming.
Passive drag	The hydrodynamic, resistive force experienced by the swimmer opposite to their direction of travel, whilst holding a fixed body position.
Body roll	The angular motion of the body about its longitudinal axis during the stroke cycle.
Intra-cyclic speed fluctuation	A measure of how much a swimmer's speed changes within a stroke cycle.
Froude efficiency	The proportion of the external mechanical power produced by the swimmer that is used to overcome active drag.

Index of Coordination	A measure of the lag time between the propulsive phases of the left and right upper limbs.
Para swimmer	Swimmer with an eligible physical, visual or intellectual impairment who has been allocated to a sport class.
Sport (S) class	The sport class in Para swimming denotes the level and type of impairment. Physical impairments are S1 to S10 with S1 being the most impaired, S10 being the least impaired.
Classification	The process used to group or 'classify' athletes with an eligible impairment into a sport class according to their degree of activity limitation owing to the impairment.
Impairment	An absence of, or substantial disparity in the body structure or bodily functions or mental functioning of an individual.
Motor coordination	The capacity to engage numerous joints and muscles in a precise, smooth and efficient manner to perform movement.
Range of motion	A measure of how much a body part can be moved around a joint or a fixed point.
Central motor and neuromuscular impairment	An umbrella term for individuals with hypertonia, athetosis, ataxia, and impaired muscle power due to health conditions such as spinal cord injury, cerebral palsy or other neuromuscular disorders.
Spinal cord injury	A traumatic injury that bruises, partially tears, or completely tears the spinal cord, damaging connections between the brain and the rest of the body.
Cerebral palsy	The name for a group of lifelong conditions that affect movement, coordination and posture, resulting from abnormal brain development or damage.
Neuromuscular disorder	A diverse set of diseases that impact the peripheral nervous system, comprising both the motor and sensory nerves linking the brain and spinal cord with the rest of the body.

Hypertonia	A condition in which there is too much muscle tone so that the upper or lower limbs are stiff and difficult to move.
Ataxia	A condition in which poor muscle control affects coordination and balance, resulting from the damage to the cerebellum.
Athetosis	A condition which is characterised by continual slow involuntary and writhing movements, resulting from the damage to the basal ganglia.

CHAPTER 1

AN INTRODUCTION TO PARALYMPIC SWIMMING AND FRONT CRAWL PERFORMANCE

The chapter provides a brief overview of the historical background of Paralympic swimming, including how it started, how it developed globally and how it became a leading sporting activity for people with disabilities. This chapter also addresses the current classification system for swimmers with a physical impairment, describes the front crawl swimming stroke and identifies key biomechanical factors that hinder front crawl swimming performance.

1.1 Para sport and the International Paralympic Committee (IPC)

The first competitive sport event for people with a disability was organised in 1948 in Stoke Mandeville, England, by Dr. Ludwig Guttmann. He pioneered a rehabilitation programme for World War II soldiers with spinal cord injuries, and he recognised the psychological and physiological value of sport within rehabilitation. The Stoke Mandeville Games were held every year from 1948 to 1959. These games laid the foundations for the modern Paralympic Games, developing from a disability sport rehabilitation program into elite sport (McCann, 1996). In 1952, The Stoke Mandeville Games became an international sporting event as ex-servicemen from the Netherlands participated and the International Stoke Mandeville Games Federation (ISMGF) was established. Swimming first appeared in the Stoke Mandeville Games in 1953 and has been included ever since.

In 1960, the first Olympic style games (the first International Stoke Mandeville Games) were held in Rome, Italy. Two hundred and nine athletes from seventeen countries competed in eight major events (archery, athletics, basketball, archery, fencing, snooker, swimming and table tennis). Thereafter, the International Stoke Mandeville Games were held every four years until 1972. With the vision of providing participation opportunities for other types of disabilities, the International Sports Organisation for the Disabled (ISOD) was founded and worked with the ISMGF to organise the 1976 Olympic Games for the Physically Disabled in Toronto, Canada. The ISOD developed the rules and classification system for athletes with limb deficiency, visual impairment, cerebral palsy and “les autres” (the others) in a wide range of sports (Tweedy et al., 2016).

The term ‘Paralympic’ did not appear until the 1988 Seoul Paralympics (Gold and Gold, 2016). In the following year, the International Paralympic Committee (IPC) was founded as the global governing body of the Paralympic movement. The word ‘Paralympic’ comprises Greek preposition ‘para’ (beside and alongside) and the word ‘Olympic’, indicating that the Paralympics are parallel to the Olympics. In 1996, the Atlanta Paralympic Games was the first time athletes with physical impairments, visual impairments and intellectual impairments all participated. However, athletes with intellectual impairments were excluded from the 2004 Athens and 2008 Beijing Paralympic Games due to the “Basketball Controversy” of the Spanish basketball team. They did not return to the Paralympics until London 2012.

To date, the IPC organises the Summer and Winter Paralympic Games and serves as the international federation for ten sports. An additional seventeen Paralympic sports are governed by independent international federations that are recognised as IPC members by the IPC. In November 2016, the IPC rebranded the ten sports it governs with new names and new identities using the World Para prefix, including World Para Swimming. The aims of the adoption were: (i) to make each Para sport more distinctive from their Olympic or non-disabled sport, (ii) to allow a more consistent and uniform promotion of Para sport, and (iii) to ensure that the Agitos, the Paralympic symbol, and the word Paralympic are only used in connection with the Paralympic Games.

1.2 Classification in Para sport – general

The purpose of classification is to evaluate inequalities in sporting excellence (Loland, 2021). Classification of athletes is not a new concept in sports. Weight, sex and age-based classes are commonly used in non-disabled sporting competitions. For athletes with disabilities, a fair classification system should objectively determine sporting performance potential by minimising the impact of an athlete’s impairment on the outcome of the event (Tweedy and Vanlandewijck, 2011). This allows athletes with a disability to have an equitable starting point for competition. Valid classification systems will ensure that the winner is the best athlete who has the most advantageous features, a combination of anthropometry, physiology, and psychology, rather than the one with the least impairment.

In the early stages of the Paralympic movement, in the 1940s, the classification system was medical based. This system grouped athletes according to their medical diagnosis. In the late 1970s, the criteria to classify athletes focused instead on the effect of impairment on specific sporting performance – the functional classification system. In this system, athletes with different physical impairments can compete together within the same class. Event organisers preferred fewer classes to reduce the complexity of event organisation. As such, the IPC implemented the functional classification system for the 1992 Barcelona Paralympic Games. However, many sports at that time had not started to develop functional classification systems. Consequently, the development of functional classification systems was time limited and therefore based substantially on expert opinion (Tweedy and Vanlandewijck, 2011) for 26 years. In 2018, IPC instructed major changes in its Classification Rules and Regulations to develop an evidence-based methods of classification.

As the Paralympic Movement has matured, the validity of the measures used in the current functional classification systems has come under increasing scrutiny. The current methods of classifying athletes are based mainly on expert opinion rather than scientific and objective evidence. This may well result in inconsistent classification decisions. It is well recognised that the degree of success a Paralympic athlete is likely to achieve is essentially influenced by their classification (Tweedy and Vanlandewijck, 2011). Classification decisions can lead to frustration, anger and the end of an athlete's career. For example, 14-time Paralympic medallist Andre Brasil filed a lawsuit against IPC after they reclassified him ineligible in 2019, and the lawsuit remains ongoing at present. Athletes may feel disadvantaged within their class or that a competitor has a significant advantage within a certain class (Burkett et al., 2018). Importantly, the substantial personal and financial cost that athletes and coaches invest into sports at the elite level as well as external rewards, such as recognition from peers and the community and commercial sponsorship (Purdue and Howe, 2012), may well be lost because of the questionable fairness of classification systems.

If individuals with disabilities are to be empowered through sports, a fair classification system is imperative. Without this, it is likely that the classification process will disempower Paralympic athletes (Howe and Jones, 2006). It is a significant threat to the entire Paralympic movement if classification systems are not perceived to be valid. The IPC recognised that providing a valid classification system for each Paralympic sport is an important and urgent challenge. Thus, in 2007, the General Assembly of the IPC approved the IPC Classification Code as a commitment to develop sport-specific classification systems that are supported by scientific evidence. Subsequently in 2009, the IPC provided guidelines to address the development of new evidence-based classification systems (Tweedy and Vanlandewijck, 2011).

The IPC Athlete Classification Code (2015) defined classification as a process which allocates athletes into groups based on the degree of activity limitation their impairment imposes on their specific sport. These groups are called “sport classes”. Within Paralympic sport, ten eligible impairment types (impaired muscle power, impaired passive range of motion, limb deficiency, leg length difference, short stature, hypertonia, ataxia, athetosis, visual impairment, and intellectual impairment) are recognised (International Paralympic Committee: Athlete Classification Code, 2015). However, not all ten impairment types are eligible to compete in all Para sports (e.g., Paracanoe only allows athletes with impaired muscle power, limb deficiency and impaired passive range of motion to compete).

1.3 Para swimming (World Para Swimming, 2022)

Para swimming is one of the most popular sports of the Paralympics and has been included at fifteen Paralympic Games since the 1960 Rome Games. At first, swimming races only included 25 m and 50 m front crawl, backstroke and breaststroke events. Longer distance 100 m races were introduced at the 1968 Tel Aviv Games. The butterfly stroke first appeared at the 1976 Toronto Games. The number of swimmers competing in the Paralympic Games has increased more than six-fold over the last fifty years (Figure 1.1), peaking at the London 2012 Paralympics with 604 swimmers from 74 countries competing in 148 swimming events. The following Paralympics, Rio 2016, housed the most countries (79) and included the most medal events (152) of the Paralympic Games.

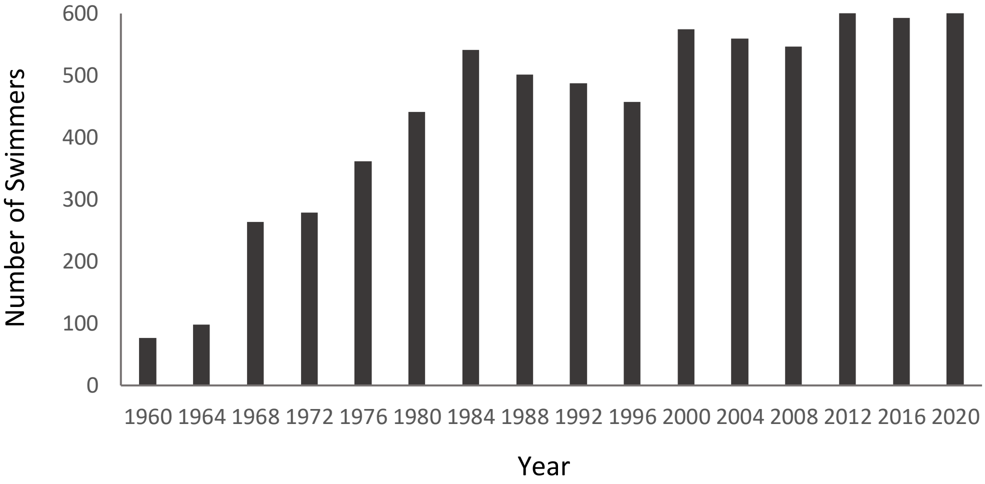


Figure 1.1: Number of swimmers that participated in the Paralympic Games from 1960 to 2020 (World Para Swimming, 2022).

Parallel to the growth in participation, the performance of Para swimmers has also improved over time. As shown in Table 1.1, the difference in 100 m front crawl swimming time between the fastest male Paralympic gold-medallist and the male Olympic gold-medallist has reduced considerably. In the 1968 Tel Aviv Games, the fastest Paralympic champion was 26.8 s slower than the Olympic gold-medallist. However, in the 2016 Rio Games the performance time gap between the fastest Para swimmer and the Olympic gold-medallist was only 3.3 s. Para swimmers have improved 28.4 s at the 2020 Tokyo Games over this period of time.

Table 1.1: Performance differences in 100 m front crawl swimming time between the fastest male Paralympic gold-medallist and the male Olympic gold-medallist.

Year	1968	1972	1976	1980	1984	1988	1992	1996	2000	2004	2008	2012	2016	2020
Paralympic	79.0	72.3	63.3	60.8	56.2	58.3	57.6	56.4	54.3	53.7	51.4	51.1	50.9	50.6
Olympic	52.2	51.2	50.0	50.4	49.8	48.6	49.0	48.7	48.3	48.3	47.2	47.5	47.6	47.0
Difference	26.8	21.1	13.3	10.4	6.4	9.7	8.6	7.7	6.0	5.6	4.2	3.6	3.3	3.6

In recent years, the term “Para swimming” has replaced the term “disability swimming” to be exclusively used to describe the elite end of the competitive sport. An individual who is a Para swimmer has an IPC Classification and is permitted to compete at a Paralympic Games or equivalent international competition. In 2017, World Para Swimming (WPS) was adopted by the IPC and introduced its World Championship events. The former championships were known as the IPC Swimming World Championships, which were held every four years. The current World Championship events are held biennially, a year after the regional championships and a year prior to the Paralympic Games. The WPS Technical Officials and International Swimming Federation (FINA) are responsible for the rules and regulations. Swimmers currently compete in events that include front crawl, backstroke, breaststroke, butterfly and individual medley, with distances ranging from 50 m to 400 m.

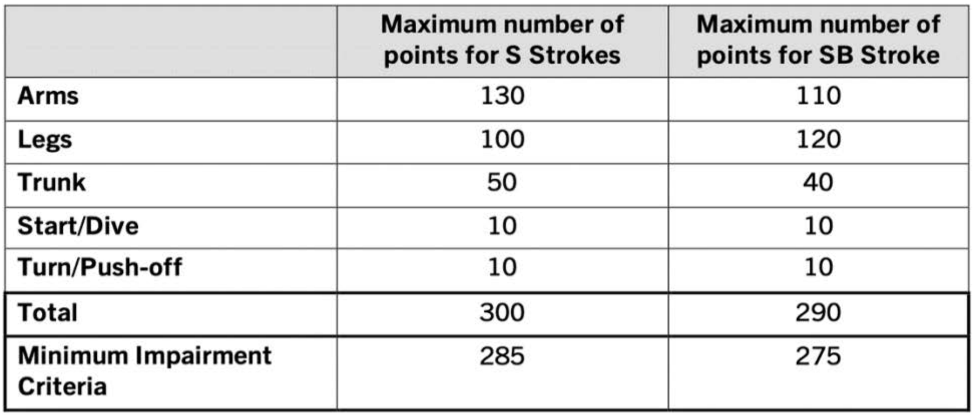
1.4 Para swimming classification (World Para Swimming, 2018)

World Para Swimming caters for three impairment groups – physical, intellectual and visual. Sport classes are separated into three stroke categories: ‘S’ strokes for front crawl, backstroke and butterfly, ‘SB’ strokes for breaststroke, and ‘SM’ denotes individual medley events. Swimmers with physical impairment are allocated to sport classes 1–10. Visually impaired swimmers are classified into sport classes 11–13 according to visual acuity, visual field and light perception, while swimmers with intellectual impairment are grouped into sport class 14 based on the results from a sport cognition test battery and observation in competition assessment.

A functional classification system is used to group athletes with an eligible physical impairment, including impaired muscle power, limb deficiency, leg length difference, short stature, hypertonia, ataxia, athetosis, and impaired passive range of motion (ROM). These impairment types must be permanent and most result from an underlying health condition (World Para Swimming, 2018). For example, spinal cord injury and spina bifida can lead to impaired muscled power and cerebral palsy and traumatic brain injury can lead to hypertonia, ataxia or athetosis. Athletes are evaluated based on the degree of their activity limitation, resulting from their impairment, as described below.

The process of the current classification for swimmers with a physical impairment comprises three components: a land-based *Physical Assessment*, a water-based *Technical Assessment* and an *Observation in Competition* assessment (World Para Swimming, 2018). The classification process aims to assess the athlete’s impairment, activity limitation and the effect of that activity limitation on swimming performance. Based on their performance in the *Physical* and *Technical Assessments*, an accumulated point system is applied which is benchmarked against the highest theoretical score a non-disabled athlete would achieve (Table 1.2). An athlete must lose a minimum of fifteen points in the *Physical Assessment* to continue to the *Technical Assessment*. It is at the discretion of the Classification Panel which tests to use. Testing focuses on the athlete's primary impairment.

Table 1.2: Maximum number of points obtainable in the *Physical* and *Technical Assessments* (taken from World Para Swimming (2018)).



	Maximum number of points for S Strokes	Maximum number of points for SB Stroke
Arms	130	110
Legs	100	120
Trunk	50	40
Start/Dive	10	10
Turn/Push-off	10	10
Total	300	290
Minimum Impairment Criteria	285	275

The total point score is then translated to determine an athlete's sport class from 1–10 for S and 1–9 for SB strokes (the SM sport class is calculated from the S and SB sport classes: [3×S + SB]/4) (Table 1.3). A lower number illustrates a more severe activity limitation than a higher number. The land-based *Physical Assessment* consists of tests in muscle strength, coordination, passive ROM, limb deficiency, body height and leg length differences. The final point score for class allocation is cumulated from each individual test with one exception that the lowest score (from impaired passive ROM or impaired muscle power) for an individual joint movement must be applied when it is affected by both impaired passive ROM and impaired muscle power (World Para Swimming, 2018). The water-based *Technical Assessment* evaluates swimmer's ability to generate propulsion, change stroke rhythms (different pacing), control and balance the streamlined body position, and perform the start and turn phases effectively (World Para Swimming, 2018).

Table 1.3: Sport class allocation on the basis of point scores obtained from the *Physical* and *Technical Assessments* and (if required) *Observation in Competition assessment* (taken from World Para Swimming (2018)).

Sport Class	Point Score	Sport Class	Point Score
S1	≤ 65	SB1	≤ 65
S2	66-90	SB2	66-90
S3	91-115	SB3	91-115
S4	116-140	SB4	116-140
S5	141-165	SB5	141-165
S6	166-190	SB6	166-190
S7	191-215	SB7	191-215
S8	216-240	SB8	216-240
S9	241-265	SB9	241-265
S10	266-285		

Previous research has demonstrated important limitations of the current functional classification system. That is, the system fails to distinguish performance clearly between adjacent classes (Burkett et al., 2018; Daly and Vanlandewijck, 1999; Oh et al., 2013; Payton et al., 2020; Wu and Williams, 1999) and may disadvantage certain impairment types within a single class (Oh et al., 2013; Payton et al., 2020). This is due to various impairment types were deemed to have the same impairment severity and competed in the same class. These studies emphasised the urgent need to make the current classification system fairer.

It is unsuitable to continue using the current methods to classify swimmers because classification results are based on the subjective opinion of clinical experts and score a swimmer's activity limitation on an ordinal scale rather than on empirical evidence. Moreover, the use of the land-based tests is dependent on the impairment type of the swimmer. The classification process is straightforward for athletes with limb deficiency, short stature and impaired passive ROM, as it requires minimal compliance from athletes. However, assessments for individuals with impaired muscle power, hypertonia, ataxia and athetosis require athletes to 'do their best'. For this reason, the validity of the tests may be jeopardised as swimmers who intend to gain an unfair advantage over their competitors might exaggerate impairment severity by purposely underperforming during classification. These shortcomings highlight the need to develop an evidence-based classification system with objective, precise, reliable and specific to the impairment measures, to prevent intentional misrepresentation and inconsistent classification decisions (Tweedy and Vanlandewijck, 2011).

The most important scientific challenge in developing a new classification system is the identification and reporting of valid and reliable measures of impairment (Tweedy et al., 2014). In 2016, WPS commissioned a series of research projects aimed at developing a new evidence-based classification system for Para swimmers. Additionally, WPS revised the water-based tests in 2018 in the middle of the Paralympic cycle. The main upgrades to the assessment are to assign the scores to different body segments on the basis of more valid and standardised tests and to access both propulsion and drag more objectively. Puce et al. (2020) monitored the change after the implementation of this classification revision in 2018 and found 35 swimmers were reassigned into a different class or the eligibility of their impairment was suddenly uncertain. The authors highlighted the significance of the World Para Swimming Classification Review Project which may further benefit the classification system from an impairment-specific approach. On the other hand, the reclassification was criticised by the president of the Brazilian Paralympic Committee, suggesting that these changes had damaged the credibility of the Paralympic sport as there was no evaluation of the impact of the decision before the changes were introduced. Incidents like this emphasise the importance of working with the Para swimming community to develop a classification system that is considered fair and valid by all. Future research should focus on establishing the relationships between impairment and swimming performance and addressing the impact of impairment on swimming performance in different strokes and distances (Burkett et al., 2018).

1.5 Classification of swimmers with central motor and neuromuscular impairment

Swimmers with central motor and neuromuscular impairment (CMNI) differ from those with anthropometric impairments (limb deficiency, short stature and impaired passive ROM). They are the athletes possessing all four limbs but with impaired motor coordination which may affect their movement pattern in the water (Hogarth et al., 2019b). CMNI swimmers are challenging to classify objectively in Para swimming, as many of the quantitative measurements required for evidence-based classification are yet to be explored (Tweedy and Vanlandewijck, 2011). These 'coordination' impaired individuals do not always complete the full battery of tests (muscle strength, passive ROM, and coordination) in classification assessments even though their health condition demonstrates a limitation in all of these parameters (Hogarth et al., 2020; Hogarth et al., 2019b; Nicholson et al., 2018).

The current assessment of passive functional ROM utilises a goniometer to directly measure the extent of joint (shoulder, elbow, wrist, finger, trunk, hip, knee, and ankle) movement possible then converts the joint angle to a point score from 0 to 5 (World Para Swimming, 2018). Conversely, an ordinal scale, six grade system (0–5) is used to evaluate muscle strength using Manual Muscle Testing (MMT) techniques where the swimmer is marked by the ability to contract their muscle around joints against an applied resistance from the classifier (World Para Swimming, 2018). While these two assessment approaches are inexpensive and widely utilised, their questionable reliability and point scale systems make them difficult to form meaningful relationships with swimming performance (Beckman et al., 2017; Evershed et al., 2012).

Of particular concern is the difference between passive ROM measurements and active ROM achieved during swimming (Nicholson et al., 2018). Active ROM measures from analysis of non-disabled swimmers should be the reference angles within passive ROM assessment. Nicholson et al. (2018) proposed a new active ROM test battery for Para swimmers as passive measures were found to be less reliable than active ROM measures, especially in the glenohumeral joint (Boon and Smith, 2000; Cools et al., 2014; De Winter et al., 2004; Muir et al., 2010). Studies have reported a lack of association between passive and active ROM in for gait (Baker et al., 2016; Manella and Backus, 2011; Turner et al., 2007). Therefore, it may be that active ROM during swimming may not have a direct relationship with the current passive ROM measurements. An additional factor that may limit the relationship between these two types of ROM is spasticity. This is characterised by a velocity-dependent resistance to movement (Levitt and Addison, 2018) which may thus limit active ROM differently at different speeds.

Current coordination testing involves Para swimmers with hypertonia, ataxia and athetosis, or an eligible neurological disorder, completing sequences of alternating single-joint movements at a steady pace and at increasing speed to assess the swimmer’s ability to coordinate their limbs (World Para Swimming, 2018). They all follow the same standardised coordination testing despite different health conditions. Each movement pattern is allocated a score from 0 to 5 by an observing classifier according to the extent of their movement control, for example, a score of 2 for “severely restricted ROM, severe spasticity-hypertonic muscle stiffness and/or severe coordination problems” (World Para Swimming, 2018). This ordinal-scaled data and subjective judgement makes it difficult to quantify impairment severity and therefore to determine the measurement weighting and aggregation in swimming classification

(Hogarth et al., 2019b; Maia et al., 2021). A recent study (Hogarth et al., 2019a) revealed that most Para swimmers with hypertonia were classified based on coordination testing alone. However, strength impairments were also found to affect swimming performance in this population group. Furthermore, as hypertonia often causes a level of spasticity, this might also constrain swimming performance by reducing ROM and motor coordination. Thus, it is essential to include the results of a full test battery for these swimmers. The authors suggest that the implementation of Para classification test batteries should be used based on athlete's aetiology of impairment.

Motor coordination is an ability to activate multiple joints and muscles to execute accurate, smooth and efficient movement (Shumway-Cook and Woollacott, 2014). To manage these reactions, it requires somatosensory, visual, vestibular input and a fully intact neuromuscular system from the motor cortex to the spinal cord (Ghez and Krakauer, 2000). CMNI is an umbrella term to describe individuals have an eligible impairment type such as impaired muscle power, hypertonia, ataxia and athetosis, resulting from an underlying health condition of traumatic brain injury, cerebral palsy, spinal cord injury or other neuromuscular disorder (Blondis, 2004; Payton et al., 2020; Santana et al., 2023). These underlying health conditions might result in awkward, extraneous, uneven, or inaccurate movement characteristics (Schmitz and O'sullivan, 2013). The activity limitations that this population exhibit usually vary considerably according to the type, the severity, and location of central nervous system pathology.

CMNI comprises highly heterogeneous clinical syndromes (Aisen et al., 2011; Benditt, 2019; Fawcett et al., 2007) resulting from injury to the brain/the connections between the brain and the rest of the body/the peripheral nervous system between the brain and spinal cord with the rest of the body. For instance, the motor characteristics are determined by the types of cerebral palsy (spastic, hypotonic, athetoid, ataxic, and mixed) may show traits including jerks, occasional clonus, stiffness, involuntary motion, fluctuations of muscle tone, poor stabilisation of the head and trunk, fatigue and absent or atypical postural mechanisms (Levitt and Addison, 2018). The level and pattern of spinal cord injury determine the loss of motor and sensory function (Bennett and Emmady, 2020), such as affected muscle strength, stiffness, decreased ROM, neurogenic pain, and prolonged movement time in the upper and lower extremity and the trunk (Mateo et al., 2015). Neuromuscular disorder, similarly, may feature characteristics like loss of strength and endurance, muscle cramps and weakness, fatigue, stiffness and pain in the neck, trunk and limbs due to an abnormality exists in any lower motor neuron components (McDonald, 2012). Although these manifold syndromes derive from different pathologies, overlapping activity limitations can be found in this population.

Several research studies have focused on how CMNI influences movement in land-based sports, reporting impaired ROM (Connick et al., 2015), reduced body strength (Beckman et al., 2016), poor motor coordination (Roldán et al., 2017), ankle and foot deformities, pain, muscle spasms and maximal exertion (Runciman and Derman, 2018). Surprisingly, similarities were found in the fatigue profiles of Para athletes with cerebral palsy and non-disabled athletes, suggesting that high level athletic training may overcome deficits associated with cerebral palsy (Ferreira et al., 2016). Yet very little is known about the challenges that Para swimmers with CMNI have in the water (Feitosa et al., 2019; Payton et al., 2020; Satkunskienė et al., 2005). It is necessary to gain a greater understanding of how CMNI influences swimming movement athletically and medically in order to classify this population.

The process advocated by the IPC to achieve an evidence-based classification system is illustrated in Figure 1.2 (Tweedy et al., 2016). These steps are based on the IPC Position Stand and a published diagram (Tweedy et al., 2014) and describe the process that should be employed. For CMNI, Tweedy and his colleagues have conducted a series of studies on developing valid measures of impairments to address ROM, muscle strength, and motor coordination (Hogarth et al., 2019a; Hogarth et al., 2019b; Nicholson et al., 2018). This thesis will contribute to the limited body of knowledge on the swimming performance determinants in individuals with CMNI. Scientific advances in these areas will enhance transparency and strengthen Para swimming classification systems.

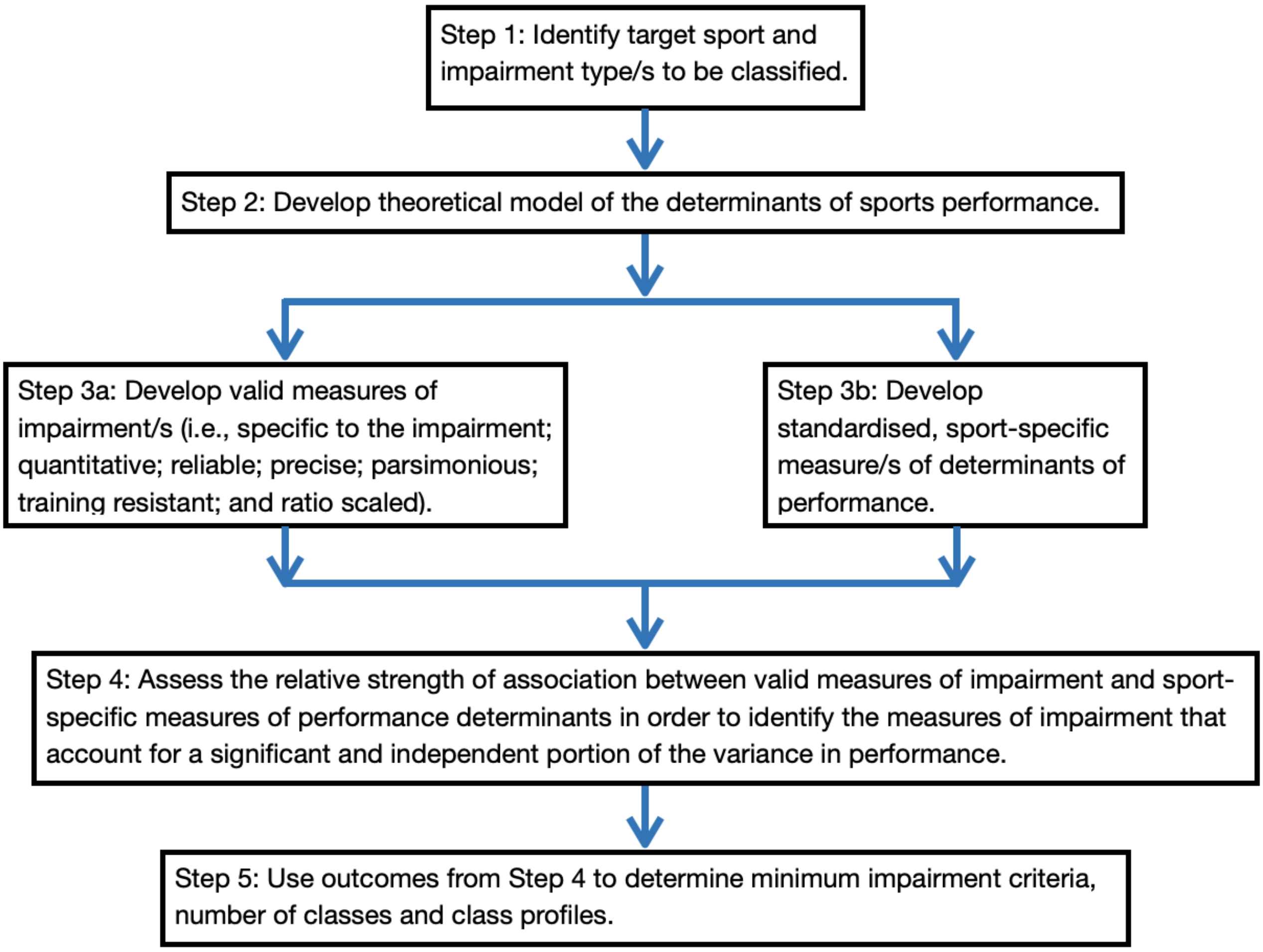


Figure 1.2: Schematic representation of the research required for the development of evidence-based systems of classification (Tweedy et al., 2016).

1.6 Front crawl swimming

Freestyle swimming races that are pool based range from 50 m to 1500 m, with the maximum distance event in Para swimming being 400 m. Swimmers can use any of the four swimming strokes in these events. However, front crawl is the swimming stroke most commonly employed in freestyle events as it is the fastest and most efficient of the four competitive strokes (Barbosa et al., 2010; Craig et al., 1985). Since front crawl is the most commonly used stroke in freestyle events, the term freestyle is often used synonymously with front crawl.

Scientific research has focused mainly on the front crawl stroke in order to understand and develop swimming performance. This is likely because it is the fastest swimming stroke and the only one to have been swum at every modern Olympic Games. Front crawl requires a series of coordinated movements from multiple body parts to propel the body forward in the water, with rhythmic and synchronised motions (Dadashi et al., 2016; Mezêncio et al., 2020). The technique involves flutter kicking with the lower limbs whilst reaching forward with cyclic and asynchronous left and right upper limb movements (Osborough et al., 2015). In Para swimming however, the swimmer’s technique might need to be adapted to compensate for any activity limitation resulting from the individual’s impairment.

Freestyle events are contested in all 10 physical impairment classes, but it would be inappropriate to compare the regular front crawl to an adapted front crawl. In the higher classes (less impaired) front crawl is used in freestyle events, whereas in some of the lower classes athletes are unable to perform the front crawl technique. For example, hemiplegia and diplegia are common conditions in athletes with CMNI where one side of the body is affected or both legs are affected; these athletes might use double arm backstroke in freestyle events. Therefore, it is important to evaluate the extent to which the type and severity of impairment causes the athlete to either: (i) adapt the front crawl, or (ii) use a completely different technique.

1.6.1 Factors limiting front crawl performance

In the Olympics, the fastest performance time in the men’s 100 m freestyle event is 47 s (International Olympic Committee, 2023), while the fastest 100 m time recorded in Para swimmers with a physical impairment is 50 s and the current fastest time in lower classes (S5 or below) is 68 s (World Para Swimming, 2023). It is interesting to note that the fastest Para swimmers are approximately 10% slower than Olympic swimmers. Naturally, there is variability within Para swimming performance times due to the increasing or decreasing impairment severities. That is, according to the records, those who are more severely physically impaired (i.e., class S5 and below) are around 25% slower than less impaired swimmers (S6–S10). One of the questions driving research in the area of Para swimming classification is what factors limit the performance of Para swimmers with CMNI. A swimmer’s performance time is largely dependent on their capacity to maximise propulsion and minimise resistance from the water (Figueiredo et al., 2013a). Whether CMNI limits propulsion, increases drag, or both, is an important consideration. Furthermore, the movement parameters that swimmers with CMNI are unable to demonstrate in order to optimise swimming performance, compared to non-disabled swimmers, are yet to be reported.

In general, the factors that limit a swimmer’s performance can be classified as physiological, morphological, biomechanical and psychological (Toussaint and Beek, 1992). Scientific research has established a number of biomechanical factors that influence front crawl swimming performance of non-disabled swimmers. These include buoyancy (Yanai and Wilson, 2008), hydrodynamic drag (Gonjo et al., 2020; Oh et al., 2013), mechanical work (Barbosa et al., 2010; Figueiredo et al., 2011), power

(Gatta et al., 2018; Peterson Silveira et al., 2019), Froude efficiency (Figueiredo et al., 2013a; Gonjo et al., 2020; Zamparo et al., 2020), propulsion (Kudo et al., 2023; Van Houwelingen et al., 2017), stroke frequency and stroke length (Kjendlie et al., 2004; Morais et al., 2022). These factors will be discussed in more detail in chapter 2. In order to quantify the degree of activity limitation experienced by swimmers with CMNI, these biomechanical factors need to be explored according to the impairment type and impairment severity. A greater understanding of how front crawl swimming performance is affected by CMNI will help in the development of a more objective evidence-based classification system.

Besides the key biomechanical factors that impact swimming performance in competition, some exercise-related challenges may also impair individuals with CMNI during front crawl movements. First, spasticity, a common condition among people with cerebral palsy, is associated with impaired muscle strength and reduced ROM, which can impact swimming performance (Hogarth et al., 2019a). This condition is characterised by an abnormal velocity-dependent increase in the muscle tone, which presents as stiff and jerky movements with exaggerated muscle contractions (Levitt and Addison, 2018), and occurs particularly during competition. Second, individuals with cerebral palsy required higher energy cost to synchronise their movements than non-disabled individuals (Brunton and Rice, 2012), this may reduce stroke frequency and stroke length, increase the duration of the breathing action or affect pacing strategy in long distance events. Third, the body parts that are affected may not be functional to generate propulsion or decrease drag. For instance, swimmers with hemiplegia or diplegia might have difficulties remaining streamlined in the water and/or need to roll their trunk more to execute a breathing action.

1.7 Overview of the research area

In the past thirty years, only a few studies have explored the performance characteristics of swimmers with CMNI. These studies all focused on the front crawl stroke, with most examining physically impaired swimmers as one group despite a broad range of impairment types (Daly and Vanlandewijck, 1999; Dingley et al., 2014; Junior et al., 2018; Pelayo et al., 1999; Santos et al., 2019). Swimmers with CMNI were rarely treated as one specific population to investigate the impact of impairment type and severity on swimming performance, other than in these five studies (Feitosa et al., 2019; Payton et al., 2020; Santos et al., 2020b; Santos et al., 2020a; Santos et al., 2017; Satkunskienė et al., 2005), with only three of those studies utilising detailed three-dimensional motion analysis (Feitosa et al., 2019; Santos et al., 2020b; Santos et al., 2017). As such, very little is known about how CMNI influences a swimmer's movement in the water.

Freestyle swimming speed is influenced more by stroke length than by stroke frequency in physically impaired swimmers, with shorter stroke lengths associated with more impaired swimmers (Daly and Vanlandewijck, 1999; Feitosa et al., 2019; Pelayo et al., 1999; Santos et al., 2019; Satkunskienė et al., 2005). Thus, in order to maximise speed, emphasising a high stroke frequency may be a strategy adopted by lower class swimmers (Junior et al., 2018; Santos et al., 2019; Satkunskienė et al., 2005). Higher bilateral strength asymmetry has been identified in swimmers with more severe physical impairments (Dingley et al., 2014). However, CMNI swimmers seem to compensate for this by altering their upper limb trajectories between the left and right sides (Santos et al., 2019).

Upper limb trajectories have previously been explored using three-dimensional (3D) motion analysis in physically impaired swimmers (Santos et al., 2019; Santos et al., 2020b; Santos et al., 2017) to highlight technique differences between swimmers. A recent 3D motion analysis study concluded that physically impaired swimmers demonstrate an increase in propulsive phases for the dominant arm and a decrease in stroke frequency after repetitive high intensity swimming (Santos et al., 2020a). The common limitation of these studies is that they did not establish whether the degree of activity limitation was related to the swimmers' impairment type and impairment severity. Thus, it remains to establish the relationship between CMNI and a swimmer's performance.

Two studies took an impairment-specific approach to address the link between CMNI and front crawl swimming performance. Feitosa et al. (2019) first discovered that more physically impaired swimmers seemed to have higher speed fluctuation within a stroke cycle and lower Froude efficiency than less impaired swimmers. Although the authors provided possible reasons for the connection between the impairment and their speed fluctuation and Froude efficiency individually, with the small sample size of CMNI swimmers (n = 4), the paper does not specify the relationships between these two parameters and sport class in this population. Payton et al. (2020), on the other hand, determined that active drag can differentiate between performance level and impairment severity. More impaired swimmers created a higher amount of both passive and active drag when swimming, especially those athletes in a sport class below S7. During the swim stroke, CMNI influenced passive drag and the swimmer's ability to interact with the water, indicating that CMNI limits swimming speed by affecting both propulsion generation and drag reduction. Together with the study undertaken by Oh et al. (2013), these studies provide evidence that a range of passive and active drag levels exist among Para swimmers within individual sport classes. This is a result of different impairment types competing within a single class, which suggests that the current classification system disadvantages some swimmers with certain impairment types. It was recommended that the assessment of drag forces may feature as a new criterion to classify CMNI swimmers.

This chapter provides a summary of the relevant research surrounding swimming performance in the population of swimmers with CMNI. The understanding of the impact that CMNI has on swimming movements is limited and insufficient at present. Future studies should identify how this group of swimmers coordinate their movements during front crawl swimming and how the key performance determinants of the front crawl swimming stroke are influenced by the type and severity of their swimming-specific impairment.

1.8 Structure of this thesis

Following this introduction, this thesis comprises a further eight chapters: a review of the literature, general methods, five experimental studies and a summary, applications, and recommendations section.

1.8.1 Chapter 2 – Literature Review

This chapter provides an extensive review of the literature surrounding the biomechanical characteristics of front crawl swimming, including relevant theoretical background and critical appraisals of scientific research. Studies on the key kinematic variables associated with front crawl performance in non-disabled swimmers are reviewed. Studies on physically impaired swimmers and WPS classification are also evaluated critically.

1.8.2 Chapter 3 – Study 1

This chapter characterises the stroke parameters of highly trained swimmers with central motor and neuromuscular impairment, using race analysis data sourced from a London Paralympic Games 2012 performance analysis project and from Great Britain Para swimming's NEMO database. This chapter also investigates the relationship between stroke parameters and central motor and neuromuscular impairment. Chapter 4 relates to academic aims i and iii, in section 2.9.

1.8.3 Chapter 4 – General methods

This chapter provide details of the full-body three-dimensional motion analysis employed in study 2, 3, 4 and 5. Information regarding the participants, experimental protocol, experimental set-up and data processing are presented. Researched variables and statistical analysis are presented within each corresponding study.

1.8.4 Chapter 5 – Study 2

This chapter compares basic front crawl kinematic variables between non-disabled swimmers and swimmers with central motor and neuromuscular impairment. In addition to this, this chapters examines the relationship between central motor and neuromuscular impairment and kinematic variables. Chapter 5 relates to academic aims ii and iii, in section 2.9.

1.8.5 Chapter 6 – Study 3

This chapter addresses body roll kinematics in non-disabled and central motor and neuromuscular impaired swimmers. The chapter also attempts to group impaired swimmers based on the level of the severity of their upper and lower limbs, establishing the impact of central motor and neuromuscular impairment on body roll kinematics in front crawl. Chapter 6 relates to academic aims ii and iii, in section 2.9.

1.8.6 Chapter 7 – Study 4

This chapter examines Froude efficiency, index of coordination and speed fluctuation, key determinants of front crawl performance, in non-disabled and central motor and neuromuscular impaired swimmers. The chapter demonstrates the effect of impairment severity and effect of elite level of central motor and neuromuscular impaired swimmers on these performance determinants. Chapter 7 relates to academic aims ii and iii, in section 2.9.

1.8.7 Chapter 8 – Study 5

This chapter quantifies the kinematic variables in double-arm backstroke, a specialist freestyle technique, in three swimmers with severe central motor and neuromuscular impairment and a group of non-disabled swimmers. This chapter assesses the characteristics of the two groups and the effects of severe central motor and neuromuscular impairment on double-arm backstroke performance. Chapter 8 relates to academic aim iv, in section 2.9.

1.8.8 Chapter 9 – Summary, implications, and future research directions

This chapter summarises the main findings of this thesis. It considers the implications of the findings to the development of a new WPS classification system for swimmers with central motor and neuromuscular impairment. It concludes with important suggestions for future research in Para swimming.

CHAPTER 2

LITERATURE REVIEW

The aim of this literature review is to provide a critical appraisal of scientific research on front crawl stroke kinematics in swimmers with and without central motor and neuromuscular impairment (CMNI). There are a large number of studies on swimming biomechanics in non-disabled populations; in contrast, the number of published studies focused on swimmers with physical impairments generally, and CMNI specifically, is extremely limited. Within this review the key kinematic variables relevant to front crawl swimming performance will be defined, the methods for measuring these variables will be discussed, and previous research on these variables will be critically evaluated. The most challenging part of developing an evidence-based classification system in Para sports is to determine the strength of association between severity and type of impairment and key determinants of performance (Tweedy et al., 2016). This review will assess the key biomechanical determinants of front crawl swimming performance and discuss how the severity and type of physical impairment affect these determinants. In doing so, it will identify criteria which might potentially be suitable for differentiating the impact of impairment type and impairment severity on swimming performance in athletes with a central motor and neuromuscular impairment.

2.1 Overview of swimming biomechanical determinants

Swimming is a form of locomotion which requires the action of fluid forces on the body to move the swimmer forward in the water. Sport biomechanics involves the application of mechanics to sports movements (Bartlett, 2014). With the complex trunk and limb movements involved in swimming, sport biomechanics can play an important role in explaining swimming movements and maximising performance. Figure 2.1 shows a theoretical (deterministic) model of critical biomechanical factors that determine front crawl performance. This model establishes the link between the movement outcome (race time) and the biomechanical variables responsible for this measure (Chow and Knudson, 2011). Given that swimmers with a CMNI may experience impaired range of motion (Connick et al., 2015), reduced body strength (Beckman et al., 2016), and/or poor coordination (Roldán et al., 2017), it can be argued that CMNI could negatively influence many of the variables shown in the model including those that determine the swimmer's average stroking (swimming) speed.

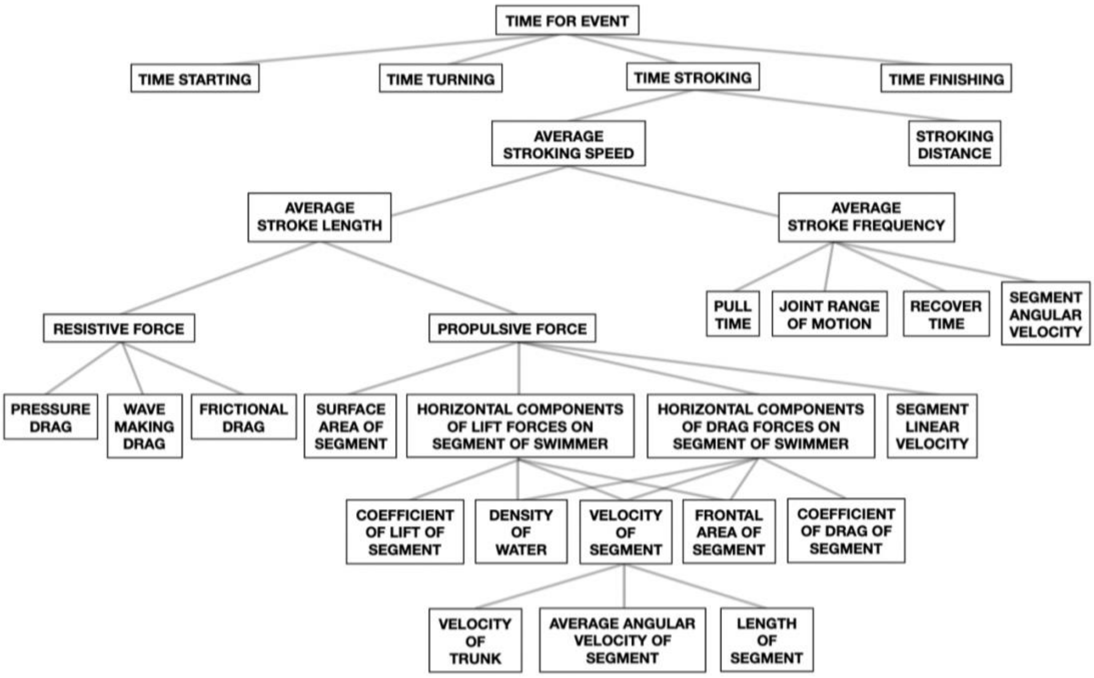


Figure 2.1: Theoretical framework identifying the biomechanical factors in swimming. Taken from Grimston and Hay (1986).

Stroking time depends on the swimmer's speed, where swimming speed (v) is the product of their stroke length (SL) and stroke frequency (SF) (Craig and Pendergast, 1979; Hay, 2002):

$$v = SL \times SF \quad [2.1]$$

where stroke frequency is defined as the number of stroke cycles, here is referred to as strokes, a swimmer completes in 1 second (Hz) and stroke length is defined as the distance a swimmer progresses within a stroke (m) (Craig and Pendergast, 1979). A stroke is a complete cycle of the upper limbs from one hand entry to the water to the next same hand entry.

In non-disabled front crawl, the higher swimming speed of faster swimmers is mainly due to their ability to achieve a greater stroke length, indicating they may generate better propulsion compared to slower swimmers (Morais et al., 2022). As front crawl swimming speed increases, stroke frequency also increases while stroke length tends to maintain at moderate pace and then decrease at sprint pace (Zamparo et al., 2020). Typically, non-disabled competitive swimmers display stroke frequency values in the range of 38–52 stroke·min^{-1} and stroke length values ranging from 2.0–2.3 m, when tested at swimming speeds ranging from 1.41–1.70 m·s^{-1} (Alberty et al., 2005; Figueiredo et al., 2013a; Gonjo et al., 2021; McCabe and Sanders, 2012).

Studies exploring front crawl stroke parameters in physically impaired swimmers have reported that stroke length is more related to swimming speed than stroke frequency is, at a sprint pace, while more impaired swimmers have shorter stroke lengths than less impaired swimmers (Daly and Vanlandewijck, 1999; Feitosa et al., 2019; Pelayo et al., 1999; Santos et al., 2020a; Satkunskienė et al., 2005). Santos et al. (2019) analysed eight Para swimmers from sport classes 5–9 performing front crawl at swimming speeds from 1.09–1.49 m·s^{-1}. Stroke frequencies and stroke lengths ranging from 48–67 stroke·min^{-1} and 1.18–1.59 m, respectively, were reported. These results highlight that Para swimmers may had difficulties in achieving the same stroke lengths as non-disabled swimmers, but not the same stroke frequencies.

Stroke length is a function of the net horizontal force acting on the body during swimming (Figure 2.1). This net force can be determined from the swimmer's horizontal acceleration using Newton's Second Law:

$$\Sigma F \ (Horizontal\ Forces) = m \times a \qquad [2.2]$$

which can be expressed as:

$$F_P - F_R = m \times a \qquad [2.3]$$

where F_P is the propulsive force, F_R is the resistive force, m is the swimmer's body mass, and a is the horizonal acceleration of the swimmer (Toussaint and Beek, 1992). When swimming at a constant speed ($a = 0$), the magnitude of the propulsive force and resistive force are equal in magnitude but opposite in direction.

Propulsion (or the propulsive force) is the sum of the hydrodynamic forces acting on the body in the swimming direction, created by the swimmer's movements in the water (Vorontsov and Rumyantsev, 2000). The resistive (drag) force is the sum of the hydrodynamic forces acting on the swimmer's body in the direction opposite to the swimming direction (Lyttle et al., 1998). Propulsive and resistive forces will be discussed in the following sections.

2.1.1 Lift and drag

Drag is a component of the hydrodynamic force in the opposite direction to a swimmer's movement (Berger et al., 1995). Drag can act in any direction which can influence swimming performance positively (propulsion) or negatively (resistance). According to the hydrodynamic theory, another factor determining swimming performance is the lift force. Lift is a force generated by pressure differences between two sides of the object, directed from areas of higher pressure to those of lower pressure (Babinsky, 2003). It always acts perpendicular to the direction of drag force (Barthels and Adrian, 1975). In swimming, the lift force is generated by asymmetrical shape of the moving limbs or the limb creates an angle of attack to the water (Bixler and Riewald, 2002) (See Figure 2.2). The angle of attack is the angle formed by the orientation of the propelling surface relative to its direction of motion.

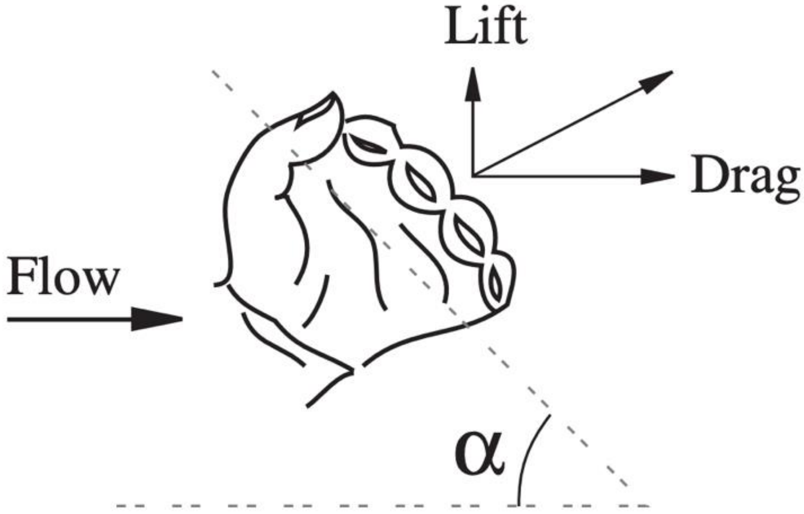


Figure 2.2: Illustration of lift and drag forces acting on the hand. α represents the angle of attack. Taken from Toussaint et al. (2000).

The drag force (D) and lift force (L) generated by the hand are expressed as:

$$D = 1/2 \cdot C_D \cdot \rho \cdot \mathrm{A} \cdot v^2 \quad [2.4]$$

$$L = 1/2 \cdot C_L \cdot \rho \cdot \mathrm{A} \cdot v^2 \quad [2.5]$$

where C_D is the drag coefficient, C_L is the lift coefficient, ρ is the density of the water, A is the hand's surface area, and v is the hand's velocity relative to water

(Toussaint, 2000). These equations show the lift and drag forces depend on the shape, size, speed, and movement direction of the body segment (Ungerechts and Arellano, 2011). Lift and drag are the components of the hydrodynamic force acting (Azuma, 2012) (e.g., on the hand). They can contribute to the overall propulsion if the forces are in the swimming direction, or to the resistance if the forces are in the opposite to the swimming direction, or to neither if the forces are in vertical or medio-lateral directions.

2.2 Propulsion

2.2.1 Mechanics of propulsion

Propulsion in swimming involves a combination of lift and drag forces but scientists continue to debate which of these components of the hydrodynamic force dominates swimming propulsion and, more importantly, what the mechanism is for generating propulsion (Rushall, 1994; Sanders, 1998). Researchers have tried to apply Newtonian mechanics (Sprigings and Koehler, 1990), Bernoulli’s principle (Schleihauf, 1979), vortex theory (Colwin, 1992) and other mechanisms, e.g., ‘pumped-up propulsion’ (Toussaint et al., 2002) to explain how swimmers propel themselves.

Upper limb propulsion was first studied through underwater observation in the late 1960s by Counsilman (1968). He suggested that front crawl swimmers push back against the water using a curvilinear path – a three-dimensional movement (Figure 2.3). With the use of this ‘S-shaped’ underwater stroke, he reasoned that swimmers could gain more propulsion with less muscular force. Swimmers at the time were advised to accelerate the body forward by pushing water directly backward. Thus Newton’s third law of motion was applied to swimming propulsion (Counsilman, 1968) and it was believed that the forward directed drag (reaction) force on the hand, created by backward hand movement, was the source of propulsion. This ‘propulsive drag theory' was soon revised by Brown and Counsilman (1971) when they acknowledged that swimmers did not move their hands solely backwards. They suggested that the prominent lateral and vertical underwater hand motions were important for propulsion. They proposed that Bernoulli's principle might be applicable as a propulsive mechanism and that during the lateral and vertical 'sculling' motions, the hand was acting as a hydrofoil to generate forward directed lift forces that, combined with forward directed drag forces, contributed to propulsion (Brown and Counsilman, 1971).

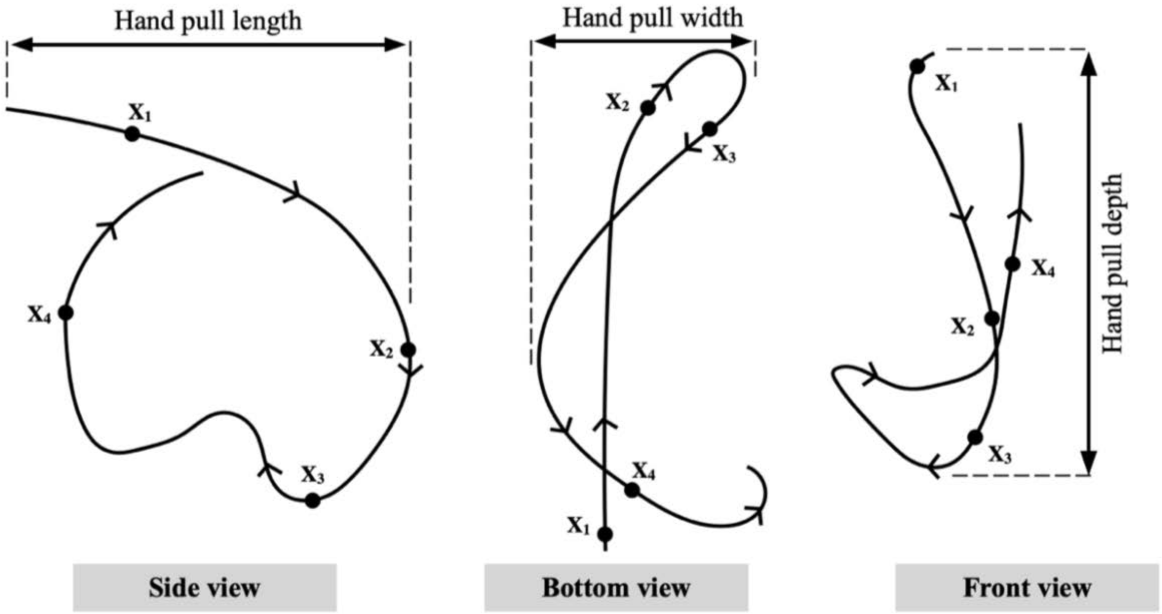


Figure 2.3: Three dimensions of the right hand trajectory relative to the water in front crawl; Glide (X_1–X_2); Pull (X_2–X_3); Push (X_3–X_4); Recovery (X_4–X_1). Adapted from Toussaint and Truijens (2005) and McCabe et al. (2015).

Later work by Schleihauf (1979) quantified the lift and drag forces acting on hand models mounted in a water channel and concluded that Bernoulli's principle was applicable, showing that both lift and drag contributed to propulsion. More recently, researchers have challenged the suitability of Bernoulli's principle for explaining lift force generation by the hand in swimming (e.g., Bixler and Riewald (2002)) and have proposed alternate theories such as the vortex theory (Colwin, 1992) and 'pumped-up propulsion' (Toussaint et al., 2002). Whilst the exact mechanism of propulsion generation in swimming remains an interesting topic of debate amongst scientists, an equally important challenge is how to obtain reliable and valid measures of propulsion (Wei et al., 2014).

2.2.2 Measurement of propulsion

Front crawl swimming is a technique that relies predominantly on the upper limbs for propulsion, with the hand and forearm segments contributing about 85% of the total propulsion (Toussaint and Beek, 1992). One of the key determinants of elite swimming performance is propulsion (Toussaint and Truijens, 2005) so naturally this fluid dynamic force has been scrutinised by many researchers over the past five decades.

Direct measurement

One way to estimate propulsive forces in front crawl involves combining three-dimensional hand kinematics (Schleihauf, 1983) with hand lift and drag coefficients obtained from hand model experiments (Schleihauf, 1979) using standard fluid dynamics equations (equations 2.4 and 2.5). With this approach, Schleihauf provided in-depth examinations of the hydrodynamic forces acting on the hand in elite swimmers and revealed that the maximum propulsive force took place near the end of the underwater stroke and the hand produced ~48 N mean propulsive force at a swimming speed of 1.66 $m \cdot s^{-1}$. Skilled swimmers were able to combine both lift and drag force in the swimming direction by constantly changing the angle of attack of the sculling hand, with their fastest hand actions in medio-lateral and vertical directions.

Although Schleihauf's method can provide insights into propulsion generation in swimming, the forces reported by Schleihauf (1983) were 10% lower than those from the MAD system (Hollander et al., 1986). As Schleihauf’s hand model lift and drag coefficients were assessed under steady flow conditions in a water channel, Toussaint et al. (2004) suggested that these differences may be due to an assumption of Schleihauf (1979) that the coefficients can be used to estimate hydrodynamic forces in swimming. Elite swimmers’ hands undergo constant changes in angle of attack, sweepback angle, direction and speed, relative to the water (Schleihauf, 1983), therefore the flow conditions encountered by the hand with these accelerations will be highly unsteady. As such, Schleihauf’s coefficients may not be valid for determining hydrodynamic forces (Lauder and Dabnichld, 2020; Pai and Hay, 1988).

Tethered swimming involves a swimmer being attached to an inelastic cord while the other end connects to a stationary force transducer which measures the propulsive force during swimming. As the swimmer is stationary, there is negligible resistive drag on the swimmer and so the recorded force can be considered the propulsive force being generated. In front crawl, the average tether forces in male swimmers range from 98.8–112.7 N (Morouço et al., 2015; Morouço et al., 2014), in female swimmer range from 71.0–74.0 N (Lee et al., 2014; Morouço et al., 2015) and in a mixed group range from 76.8–188.6 N (Hogarth et al., 2020). Although this method shows high reliability (Kjendlie and Thorsvald, 2006), the propulsive force may be overestimated compared to the real swimming condition (Samson et al., 2018) and the stroke patterns used in tethered swimming show subtle differences to those in free swimming (Psycharakis et al., 2011; Yeater et al., 1981).

Two studies have used tethered front crawl swimming to investigate propulsive force in Para swimmers. One examined nine S9 unilateral arm-amputee female swimmers (Lee et al., 2014), the other examined 80 Para swimmers with various physical impairments from classes S1–S10 (Hogarth et al., 2020). Para swimmers with limb deficiency produced mean tethered forces of 41.8–55.7 N (Hogarth et al., 2020; Lee et al., 2014), while those with impaired muscle power and with hypertonia recorded mean forces of 63.9 N and 50.1 N, respectively (Hogarth et al., 2020). More impaired swimmers exhibited lower tether forces than less impaired swimmers, but comparable fatigue indexes existed across swimmers with and without an impairment, indicating that there is no effect of impairment type on the ability to sustain propulsive force over a 30 s test.

Indirect measurement

Since the early hand model hydrodynamic experiments of Schleihauf (1979), researchers have continued to use water channels or wind tunnels to examine hand and forearm hydrodynamic forces. More recent studies have attempted to quantify unsteady flow effects on hand and upper limb models by incorporating accelerations, rotations, or complete underwater stroke conditions (Kudo et al., 2013; Matsuuchi et al., 2009; Nakashima and Takahashi, 2012; Takagi and Sanders, 2002; Takagi et al., 2014) Using a robotic arm (Figure 2.4), Kudo et al. (2013) found that when the hand was accelerating, hydrodynamic forces were 1.9 to 10 times higher than for a non-accelerating hand. Moreover, to elucidate the human swimming propulsion mechanism, Takagi et al. (2014) applied particle image velocimetry (PIV) (see next page) to visualise the unsteady fluid forces generated by a real swimmer's front crawl sculling movement in a flow-controlled water channel. Using physical models makes it easier to reproduce trials compared to using real swimmers, yet some of these options may not be ideal due to the required instruments and software, which can be excessively costly (Barbosa et al., 2020).

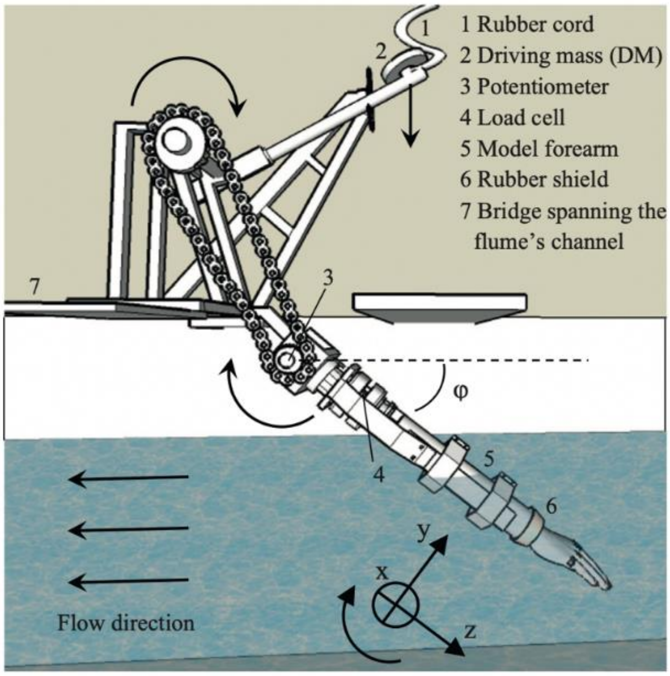


Figure 2.4: Rig for assessing hydrodynamic forces acting on the robotic hand model. Taken from Kudo et al. (2013).

Particle image velocimetry (PIV), an optical method to measure instantaneous fluid velocities, is a relatively recent method for researching fluid flow in swimming techniques (Matsuuchi, 2004; Matsuuchi et al., 2009; Takagi et al., 2013; Takagi et al., 2014). PIV can track particles in the water to measure the momentum of the flow acting around a swimmer or a body segment, e.g., hand, in detail. For instance, Takagi et al. (2014) found maximum thrust (propulsion) in an 'S-shaped' hand trajectory was lower than in an 'I-shaped' trajectory (a straighter pull), reporting values of 17.5 N and 27.5 N, respectively. PIV has clarified vortex generation as being one of the propulsive mechanisms while a swimmer changes their hand direction (Matsuuchi et al., 2009; Takagi et al., 2013; Takagi et al., 2014). This method shows potential to enable flow visualisation in a swimming pool, however, it is time consuming to calibrate the flow field and the observation area is limited to two dimensions and 1 m^2 which fails to cover the entire swimming motion at once (Takagi et al., 2016).

One of the most well-known numerical tools for assessing hydrodynamic forces in swimming is computational fluid dynamics (CFD) – a computer simulation technique that involves solving the Navier-Stokes equations of fluid flow (Ferziger et al., 2019), obtaining the velocities and pressures by using a large number of computational cells or meshes. This approach can provide a more comprehensive dataset (e.g., fluid velocities, velocity gradients, and pressure data) than real-life measurement (Van Houwelingen et al., 2017). CFD studies have revealed that the drag forces contribute substantially more to propulsion compared to the lift forces (Bixler and Riewald, 2002; Rouboa et al., 2006); propulsion is enhanced by a small finger spread (Lorente et al., 2012; Marinho et al., 2010; Minetti et al., 2009; Sidelnik and Young, 2006; Van Houwelingen et al., 2017); and lift force was greatest at an angle of attack of 45° (Marinho et al., 2009).

CFD has been used almost exclusively to investigate non-disabled swimming, with the exception of Lecrevain et al. who in 2008 used unsteady CFD to simulate the underwater stroke of a female below-elbow amputee swimmer. The upper arm produced a mean hydrodynamic force and mean propulsive force of 7.9 and 3.2 N, respectively, at a swimming speed of 1 $m \cdot s^{-1}$. In a subsequent CFD study, Lecrivain et al. (2010) investigated the effect of upper arm rotation speed and body roll on propulsion of an arm amputee swimmer at different swimming speeds. A body roll of 45° increased propulsive force from the upper arm by ~70% compared to zero body roll.

The application of CFD appears to be a powerful tool to explain the propulsive mechanisms by computing the fluid flow around a swimmer's hand, forearm or whole body. However, when attempting to simulate a swimmer in motion, it is extremely challenging to determine the flow during dynamically changing postures and limb orientations (Takagi et al., 2016). CFD simulations involve errors from turbulence models, errors from the physical modelling, and errors from the finite resolution (Takagi et al., 2016). Moreover, it is complex for CFD to simulate the air-water interface to determine the wave drag acting on a swimmer (Van Houwelingen et al., 2017). Essentially, theoretical CFD results must be evaluated by human experimental studies to determine their validity.

These indirect measurement techniques enhance our understanding of swimming propulsion by examining hydrodynamic properties for different hand orientations, shapes, sizes and velocities under different conditions (steady-state, acceleration, unsteady-state). To optimize front crawl swimming propulsion, the findings suggest that swimmers should: (i) accelerate the hand during a propulsive phase (Bixler and Schloder, 1996; Gourgoulis et al., 2015; Rouboa et al., 2006; Sato and Hino, 2003); (ii) spread fingers slightly to increase the drag coefficient (Bilinauskaite et al., 2013; Marinho et al., 2010; Minetti et al., 2009; Schleihauf, 1979); (iii) alter thumb position during the stroke depending on whether lift or drag prevails in the stroke phase (Bilinauskaite et al., 2013; Marinho et al., 2009; Schleihauf, 1979); and (iv) avoid excessive sculling (S-stroke) movements to generate higher hydrodynamic forces (Takagi et al., 2013; Takagi et al., 2014). These insights offer coaches and swimmers information to improve training and performance which cannot be obtained easily by tests on swimmers alone. Some relatively recent studies have attempted to improve understanding of human swimming by integrating numerical and experimental methodologies (Cohen et al., 2015; Nakashima et al., 2012; Sato and Hino, 2013; Takagi et al., 2014). A combination of the applications of CFD, flow visualization techniques and force measurements was recommended by Van Houwelingen et al. (2017) to produce a thorough picture of propulsive force.

2.3 Resistance

2.3.1 Mechanics of resistance

Resistance is a result of water viscosity and, at high speeds, turbulence created behind the swimmer (Toussaint et al., 2000). When a swimmer moves through the water surface, extra resistance arises from gravitational forces on the waves generated by the movement. The total resistive drag (R_{Total}) comprises three components: viscous pressure drag ($R_{Viscous\ Pressure}$), wave drag (R_{Wave}), and frictional drag ($R_{Frictional}$) (Webb et al., 2011). This is expressed as:

$$R_{Total} = R_{Viscous\ Pressure} + R_{Wave} + R_{Frictional} \qquad [2.6]$$

When the swimmer reaches a certain speed, the length of the longitudinal wave will equal the swimmer’s height. This is the same for shipbuilding science: the vessel’s speed matched with a wave that has the same length as the vessel. When reaching that speed, theoretically it becomes challenging for the swimmer to swim even faster (Vorontsov and Rumyantsev, 2000). This particular speed is called the “hull speed” which is influenced by the morphology of a swimmer. For example, taller swimmers create less wave resistance at a given speed and have a greater potential for maximal speed than shorter swimmers (Kjendlie and Stallman, 2011).

2.3.2 Measurement of resistance

The effect of drag on swimming performance can be positive (propulsion) or negative (resistance) based on the direction. Swimmer drag can be considered under two conditions: active drag is the resistance force a swimmer experiences opposite to their direction of travel while actively swimming; passive drag is the resistance force a swimmer experiences opposite to their direction of travel while holding a fixed body position (Payton et al., 2020; Vorontsov and Rumyantsev, 2008).

Passive drag

The measurement of passive drag is relatively straightforward as the swimmer holds a fixed, often streamlined, body position with no movements from the limbs or body, assuming the best position to reduce hydrodynamic forces during gliding (Scurati et al., 2019). In the literature, the towing method is the most common approach due to its validity and high reliability (Cortesi and Gatta, 2015; Mollendorf et al., 2004). One of the earliest attempts to measure passive drag was done using a dynamometer while towing the swimmer with a rowing boat (Amar, 1920). Now, swimmers are typically towed by electro-mechanical towing devices comprising a winch, cable and load cell (Lyttle et al., 2000; Oh et al., 2013). Other approaches include (i) the flume method, where passive drag is recorded on a dynamometer with the swimmer tested stationary in a large water channel with a controllable flow speed (Chatard and Wilson, 2003), (ii) the gliding velocity decay method, where passive drag is determined from the computed instantaneous deceleration during a push-off and glide from the pool wall, and the swimmer's body mass (Mollendorf et al., 2004), and (iii) computational fluid dynamics (CFD) (described in section 2.2.2) where passive drag is estimated through modelling a swimmer and the flow characteristics. Typically, values of passive drag, in a streamlined position, range from 53–72 N at swimming speeds of 1.5–1.6 $m{\cdot}s^{-1}$ (Barbosa et al., 2015; Cortesi and Gatta, 2015; Gatta et al., 2016; Narita et al., 2017). For a thorough review of measuring passive drag in swimming, the readers may refer to Scurati et al. (2019).

To date, only four studies have investigated passive drag in Para swimmers with various physically impairment types. Chatard et al. (1992) reported that the passive drag experienced by the participants (n = 34) was associated with the severity level of their lower-limb impairment (wheelchair, walking aid, no aid). The other three studies reported passive drag values of physically impaired swimmers ranging from 24.9–120 N at towing speeds of 1.5–1.7 $m \cdot s^{-1}$ (Fulton et al., 2011; Hogarth et al., 2021; Oh et al., 2013). Hogarth et al. (2021) and Oh et al. (2013), examined 132 (S1–S10) and 113 (S3–S14) Para swimmers, respectively, and examined the effect of impairment severity (sport class) on swimming performance, concluding that higher passive drag is associated with swimmers in the lower sport classes. The high passive drag variability observed within some of the lower classes indicated that some swimmers may be advantaged over others. Importantly, Hogarth et al. (2021) pointed out that swimmers with impaired muscle power, impaired passive range of movement and hypertonia may produce higher drag than other impairment types, such as those with limb deficiency. Passive drag therefore may be a useful tool in classification to assess activity limitation in swimming.

Active drag

Compared to passive drag, active drag is extremely difficult to measure directly because it includes both propulsive and resistive forces acting at the same time (Webb et al., 2011). Hence, various indirect methods have been suggested to estimate this force during front crawl swimming. The Measuring Active Drag (MAD) system was developed by Hollander et al. (1986). A swimmer propels themselves by pushing off against a series of instrumented pads located under the water surface; the push-off forces are recorded directly by a force transducer on the pool wall (Figure 2.5). Active drag is assumed to be equal to the mean hand push-off force recorded for the trial. This method is based on the assumption that swimming speed is constant. On the MAD system, front crawl swimmers display mean active drag ranging from 66.9–111 N at swimming speeds of 1.52–1.68 $m \cdot s^{-1}$ (Formosa et al., 2012; Seifert et al., 2010c; Toussaint et al., 2004). Three limitations of MAD system have been highlighted

(Havriluk, 2007): (i) testing on the MAD system requires the swimmer to propel themselves without use of their lower limbs. The absence of kick makes it unsuitable to estimate active drag in real swimming; (ii) the hydrodynamic forces between hand entry and the hand contacting the push off pads are not measured; (iii) the backward hand movement is relative to the body rather than relative to the water as the hand pushes against a fixed surface.

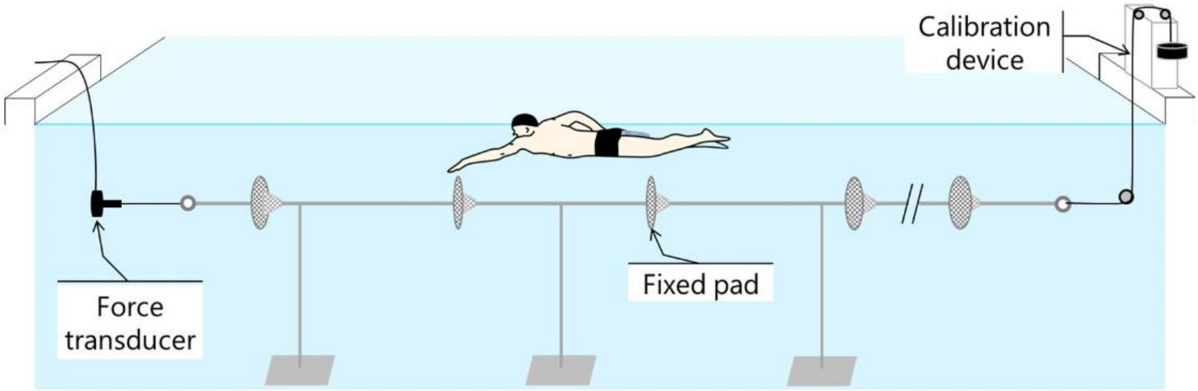


Figure 2.5: Illustration of the MAD system. Taken from Narita et al. (2018).

Other researchers have since proposed alternative approaches to the MAD system for estimating active drag in front crawl swimming. These include: (i) the velocity perturbation method (VPM) (Kolmogorov and Duplishcheva, 1992) where active drag is derived from speeds recorded during two maximal effort swims, one swimming freely, the other whilst towing an object of known additional resistance, (ii) the assisted towing method (ATM) (Alcock and Mason, 2007) where active drag is estimated from the swimmer's maximum swimming speed and the mean force required to tow them at 110% of this maximum speed, and (iii) the naval architecture based approach (NABA) (Webb et al., 2011) in which a model of a self-propulsion experiment for ships is used where active drag is determined by combining the swimmer's passive drag with the mean towing force obtained during a maximum effort swim. All of these methods provide an estimate, rather than a direct measure of active drag and they each have inherent limitations and assumptions that may affect their validity. A comprehensive review of these methods is beyond the scope of this review and the reader may wish to refer to the following review papers for more information (Haskins et al., 2023; Lopes et al., 2022).

Active drag is as an important determinant of non-disabled swimming performance (Toussaint and Beek, 1992) and is influenced greatly by a swimmer's skill level (Kjendlie and Stallman, 2008; Kolmogorov and Duplishcheva, 1992; Marinho et al., 2010), rather than by a swimmer's anthropometry, unlike passive drag. As skill level increases, swimming speed increases, so elite swimmers typically have greater active drag and power required to overcome drag than sub-elite swimmers (Kolmogorov et al., 2021; Seifert et al., 2010c; Toussaint et al., 2004; Zamparo et al., 2009). In addition, Formosa et al. (2014) found the breathing action in front crawl causes a 16–26% increase in active drag compared to non-breathing, indicating that even relatively small changes in body position can have a large influence on active drag. In the literature, the active drag of non-disabled front crawl swimmers ranges from 50–148 N at swimming speeds of 1.4–1.84 $m \cdot s^{-1}$ (Formosa et al., 2012; Kolmogorov et al., 2021; Zamparo et al., 2009).

Only two studies have explored active drag in physically impaired swimmers. The first was a case study of a swimmer with a unilateral arm amputation (Figueiredo et al., 2014) which concluded that active drag was related to the swimming speed and an increase in active drag led to an increase in her energy cost. The second (Payton et al., 2020) took an impairment-specific approach to address how CMNI impacts active drag. Seventy-two highly trained Para swimmers from sport classes S1 to S10 were tested using the NABA method (Webb et al., 2011) and it was concluded that active drag can differentiate performance level and impairment severity. More impaired swimmers created higher passive and active drag than the less impaired, especially those athletes in a sport class below S7. Together with the study undertaken by Oh et al. (2013), this research provided evidence that a range of passive and active drag levels exist amongst Para swimmers within individual sport classes due to different impairment types competing within a single class. The authors suggested that the current classification system disadvantages some swimmers with certain impairment types and that drag force may be an important criterion to classify CMNI swimmers.

2.4 Swimming energetics

Swimming performance is not solely determined by the interaction of propulsive and resistance forces. It is sometimes useful to evaluate swimming performance from an energetics perspective by analysing the work, power and efficiency of the swimmer. Forward displacement of the swimmer in the water is generated by the mechanical work done upon the swimmer by the net horizontal force. It can be expressed as:

$$W = F \cdot d \cdot cos\theta \qquad [2.7]$$

Where: W is the mechanical work done on the swimmer, F is the net force acting, d is the displacement and the angle (θ) is defined as the angle between the force and the displacement vector. The unit for W is the joule (J).

The time derivative of the work produced by the swimmer (or done on the swimmer) is the mechanical power (Toussaint and Truijens, 2005), which presents the rate of doing work. This can be expressed as:

$$P = W/t \qquad [2.8]$$

Where: P is the power, W is the work, and t is the time. Together with the Equation 2.9, it can be transformed as:

$$P = F \cdot cos\theta \cdot (d/t) \qquad [2.9]$$

Where: the d/t is the average or constant speed. Thus, it is expressed as:

$$P = F \cdot v \cdot cos\theta$$

Where: v is the average or constant swimming speed.

The total mechanical power (P_o) generated by the swimmer can be broken down into the power used beneficially to overcome drag (P_d), and the power lost in giving water a kinetic energy change (P_k) (Toussaint et al., 1988). Hence:

$$P_o = P_d + P_k \tag{2.10}$$

The ratio between the power to overcome drag (P_d) and the total mechanical power output (P_o) is defined as the propelling efficiency, where P_d at a swimming velocity (v) and the drag force (F_d) is expressed as:

$$P_d = F_d \cdot v \tag{2.11}$$

and P_k is given by:

$$P_k = 1/2 \cdot \mathrm{m}(\Delta u)^2 \cdot f \tag{2.12}$$

where m is the mass of the pushed water, Δu is the velocity change of the pushed water, and f is the stroke frequency (Toussaint et al., 1983).

The concept of efficiency in swimming is quite complex and researchers have attempted to quantify it in several ways. It is extremely challenging to quantify a swimmer's P_o, P_d and P_k accurately and validly. Therefore, researchers have proposed models (Froude efficiency) that utilise swimming speed and upper limb speed (Figueiredo et al., 2011; Gatta et al., 2018; Gonjo et al., 2018; Gonjo et al., 2020; Ribeiro et al., 2017; Zamparo, 2006; Zamparo et al., 2008; Zamparo et al., 2014) to estimate swimming efficiency. These models will be discussed in the next section.

2.4.1 Propelling and Froude efficiency

Swimming speed is a consequence of the interplay between the propulsive forces that a swimmer can generate and the resistive forces acting on the swimmer (Seifert et al., 2015). Froude/propelling efficiency represents the proportion of the external/total mechanical power produced by the swimmer that is utilised to overcome hydrodynamic resistance (Zamparo et al., 2020). Propelling efficiency (η_P) is the product of hydraulic efficiency (η_H) and Froude efficiency (η_F) (Figure 2.6). While hydraulic efficiency relates to the internal power necessary to accelerate and decelerate the limbs in relation to the centre of mass, it only represents 10–15% of the total mechanical power (Zamparo et al., 2005). Froude efficiency is therefore assumed to be the main determinant of propelling efficiency (Gonjo et al., 2020).

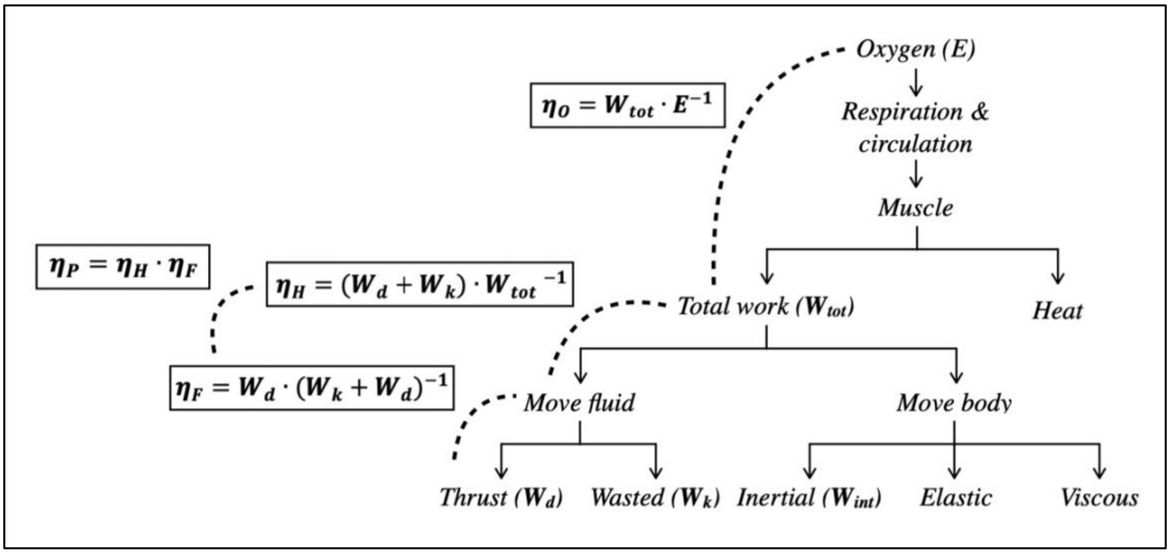


Figure 2.6: A diagram of the energy conversion and efficiency in swimming. Adapted from Gonjo et al. (2020). η_O, overall efficiency; η_P, propelling efficiency; η_H, hydraulic efficiency; η_F, Froude efficiency.

Toussaint et al. (1988) estimated Froude efficiency using the MAD system (Figure 2.5) to directly assess external power for a given metabolic power input and the power used to overcome drag for a given swimming speed. The MAD system is a controlled condition where Froude efficiency is assumed to be maximal as no power is wasted transferring the energy to the water. By comparing the energy cost of swimming front crawl on the MAD system and then freely at the same speed, an estimate of Froude efficiency was derived.

To measure a swimmer's external power and the power to overcome hydrodynamic drag under free swimming conditions is extremely difficult, so researchers have developed various mathematical models to estimate efficiency (Figueiredo et al., 2011; Martin et al., 1981; Zamparo et al., 2005). Martin et al. (1981) proposed a method of estimating Froude efficiency from kinematic data on the swimmer, defined it as the ratio between the mean forward speed of the swimmer and the mean resultant hand speed, assuming that propulsive and drag forces are equal in magnitude. Zamparo et al. (2005) adapted this theoretical model of efficiency into a simplified paddle-wheel model (Equation 2.13), which models the lower limbs as contributing 10% to the propulsion.

$$\eta_F = ((v \times 0.9) \times (2\pi \times SF \times L)^{-1})(2 \times \pi^{-1}) \tag{2.13}$$

where v is the swimming speed, SF is the stroke frequency and L is average distance from shoulder to hand during the upper limb cycle.

This paddle-wheel model has been widely used since its introduction (Gatta et al., 2018; Peterson Silveira et al., 2017; Zamparo, 2006; Zamparo et al., 2008; Zamparo et al., 2014) but some of its assumptions will limit its validity. Specifically, hand speed is not a direct input to the model but instead is estimated from an upper limb radius (L) and stroke frequency, both of which are assumed to remain constant. The hand motion is simplified to two dimensions and the model assumes that the swimmer's speed is constant throughout the upper limb cycle with no overlapping of the propulsive phases of the two upper limbs. Addressing some of the limitations of the paddle-wheel model, Figueiredo et al. (2011) developed an alternative kinematics-based model. This model of Froude efficiency requires three-dimensional hand speeds and swimmer mass centre kinematics as inputs as shown in equation 2.14 (Figueiredo et al., 2013a; Gonjo et al., 2018; Gonjo et al., 2020; O'Dowd et al., 2023).

$$\eta_F = v_{COM} \times 3Du_{hand}{}^{-1} \qquad [2.14]$$

where v_{COM} and $3Du_{hand}$ are mean velocity of the centre of mass and the sum of the mean underwater three-dimensional speed of the two hands during the upper limb cycle. The effect of lower limb motion, however, is not taken into account. Notably, these models are an estimation of Froude efficiency rather than propelling efficiency because hydraulic efficiency is not considered in these equations. To obtain propelling efficiency, a swimmer's total power output would need to be known (Zamparo et al., 2020).

Peterson Silveira et al. (2019) compared two methods of assessing Froude efficiency from video analysis (Martin et al., 1981; Toussaint et al., 1988; Zamparo et al., 2005) with a power-based Froude efficiency derived from direct measures made on the MAD system (Toussaint et al., 1988). Fourteen non-disabled swimmers swam 200 m pace front crawl using their upper limbs only. The model of Martin et al. (1981) provided the closest value to the "actual efficiency" giving a value that was 4% lower than the theoretical Froude efficiency from the MAD system. Although all methods yielded different values of Froude efficiency, Bland-Altman plots revealed they were in good agreement with each other, indicating that they may all be valid methods of estimating Froude efficiency (Peterson Silveira et al., 2019). A thorough appraisal of all the methods used to estimate the various forms of efficiency in swimming is beyond the scope of this review. The reader is directed to Zamparo et al. (2020) for a detailed review of swimming efficiency. Due to the various definitions and computational procedures, care should be taken when comparing 'swimming efficiency' values between studies.

In non-disabled front crawl swimming, Froude efficiencies ranging from 0.25 to 0.63 have been reported (Figueiredo et al., 2011; Gatta et al., 2018; Gonjo et al., 2020; Gourgoulis et al., 2008; Ribeiro et al., 2017; Toussaint, 1990; Zamparo, 2006; Zamparo et al., 2008; Zamparo et al., 2014). Froude efficiencies of 0.40 to 0.47 have been found in highly trained non-disabled male swimmers using the speed-based model from Figueiredo et al. (2011) (Figueiredo et al., 2011; Gonjo et al., 2018; Gonjo et al., 2020), with Froude efficiency increasing with decreasing swimming speed (Gonjo et al., 2020). Previous research into Froude efficiency in non-disabled front crawl swimmers has demonstrated that it: (i) is higher in faster than slower swimmers (Ribeiro et al., 2017); (ii) changes along with the development of muscle strength and power in different age groups, reaching a maximum at about 20–30 years old then steadily declines (Zamparo, 2006); (iii) increases when the propulsive area of the hand is increased by using hand paddles (Gourgoulis et al., 2008); and that (iv) a higher value is associated with a lower value of Index of Coordination (Figueiredo et al., 2013b), a slower stroke frequency (Zamparo et al., 2005) and a greater stroke length (Zamparo et al., 2005; Zamparo et al., 2014).

Only two studies have investigated Froude efficiency in physically impaired swimmers during front crawl. Feitosa et al. (2019) reported a mean value of 0.31 (range 0.19–0.40) for eleven swimmers with a wide range of impairment types and severities, tested at speeds ranging from 0.76–0.93 $m \cdot s^{-1}$, concluding that the more impaired swimmers tended to have lower Froude efficiencies than the less impaired. This study was limited by a small sample size and wide variation in physical impairment types meaning that it did not greatly improve understanding of the impact of specific impairment types on Froude efficiency. Recently, (O'Dowd et al., 2023) started to address this issue by testing a group of ten Para swimmers with the same impairment type and severity, a unilateral forearm-amputation. Mean Froude efficiencies of 0.35 and 0.37 were found at speeds of 1.31 $m \cdot s^{-1}$ and 1.17 $m \cdot s^{-1}$, respectively, and the study demonstrated that Froude efficiency was higher when propelling with the unaffected arm compared to when propelling with the residual limb. The authors suggested that Froude efficiency may be a useful metric for differentiating the type and severity of physically impaired swimmers yet no study has determined Froude efficiency in a group of CMNI swimmers. Understanding the link between CMNI and Froude efficiency in front crawl may help explain the effect of their unique movement on swimming performance.

2.5 Body roll in front crawl

Body rotation about the longitudinal axis, commonly known as body roll, is an important factor for maximising front crawl swimming performance (Counsilman, 1968; Yanai, 2001b). Previous studies have highlighted the important functions of this action: facilitating the breathing action (Payton et al., 1999; Psycharakis and McCabe, 2011), aiding recovery of the upper limb over the water (Counsilman, 1968), increasing propulsion (Kudo et al., 2017; Lecrivain et al., 2010), reducing hydrodynamic drag (Castro et al., 2003; Clarys, 1975) and reducing the risk of developing shoulder injuries (Vila Dieguez and Barden, 2020).

Body roll in front crawl swimming has been defined and analysed in various ways in the literature. In kinematic analyses it is usually represented by the rotation of a line connecting left and right shoulder and hip joints around the long axis of the trunk (Figueiredo et al., 2013; Payton et al., 1999; Psycharakis and Sanders, 2008). Thus a separate shoulder roll and hip roll are defined. Other researchers have quantified rotation of the entire body, henceforth referred to as whole-body roll, from the whole-body angular momentum of the swimmer about their long axis (e.g., Gonjo et al., 2021; Sanders et al., 2016; Yanai, 2001b). The latter approach enables an analysis of the external torques acting on the swimmer and the mechanisms creating and controlling whole-body roll. Therefore, the term 'body roll' is a broad term that refers to either the rotation of the whole-body or separate rotations of the shoulders and hips.

Analysis of whole-body roll provides an understanding of the mechanisms, specifically the torques, responsible for generating trunk rolling movements in front crawl (Yanai, 2001). The forces that determine the torques acting external or internal to the swimmer's body and contribute to body roll are: (i) hydrodynamic forces (lift and drag) in medio-lateral and vertical directions, the non-propulsive directions. These create an external torque which changes the whole-body angular momentum about the long axis (Yanai, 2001b); (ii) internal muscle forces. These apply reaction torques to the trunk in the opposite direction to those that drive upper and lower limb movements (Payton et al., 1999). These internal torques generally restrain body roll and its amplitude, rather than create it (Yanai, 2001b); and (iii) buoyancy force. This produces an external torque when the buoyancy force acts eccentric to the long axis. When the upper limb is recovering over the water, the whole-body centre of buoyancy shifts away from the whole-body centre of mass forming a turning effect about the longitudinal axis. Yanai (2004) concluded that buoyant torque is the primary source of whole-body roll in non-disabled front crawl swimming. In addition, he reported that skilled swimmers were able to use the buoyancy force more effectively than less-skilled swimmers to generate body roll.

In front crawl swimming, highly trained non-disabled swimmers exhibit shoulder roll ranging from 64–111° and hip roll ranging from 50–57° at swimming speeds of 1.41–1.47 $m \cdot s^{-1}$ (Andersen et al., 2020; Gonjo et al., 2021; McCabe and Sanders, 2012). The following characteristics of body roll in non-disabled swimmers have been reported: (i) shoulder roll amplitude is significantly higher than hip roll amplitude (Andersen et al., 2020; Cappaert et al., 1995; Psycharakis and Sanders, 2010); (ii) while hip roll amplitude decreases with an increase in the swimming speed, trunk twist (shoulder roll relative to the hip roll) increases when swimming speed increases (see Figure 2.7) (Andersen et al., 2020; McCabe and Sanders, 2012; Yanai, 2003); (iii) increased stroke frequency leads to a decrease in the whole-body roll, the shoulder roll (Gonjo et al., 2021; Yanai, 2003) and the hip roll (Andersen et al., 2020; Gonjo et al., 2021); (iv) elite swimmers roll their shoulder less than less-elite swimmers at 200 m race pace and roll asymmetry does not seem to affect swimming performance (Psycharakis and Sanders, 2008); and (v) fatigue causes an increase in hip roll but not in shoulder roll (Andersen et al., 2020; Psycharakis and Sanders, 2008). As non-disabled front crawl swimmers all use similar upper and lower limb motions, it is appropriate to draw these general conclusions regarding their rolling features. However, physically impaired swimmers often have to adapt their movement patterns to compensate for their disability so it seems likely that their body roll kinematics could differ considerably from those of non-disabled swimmers.

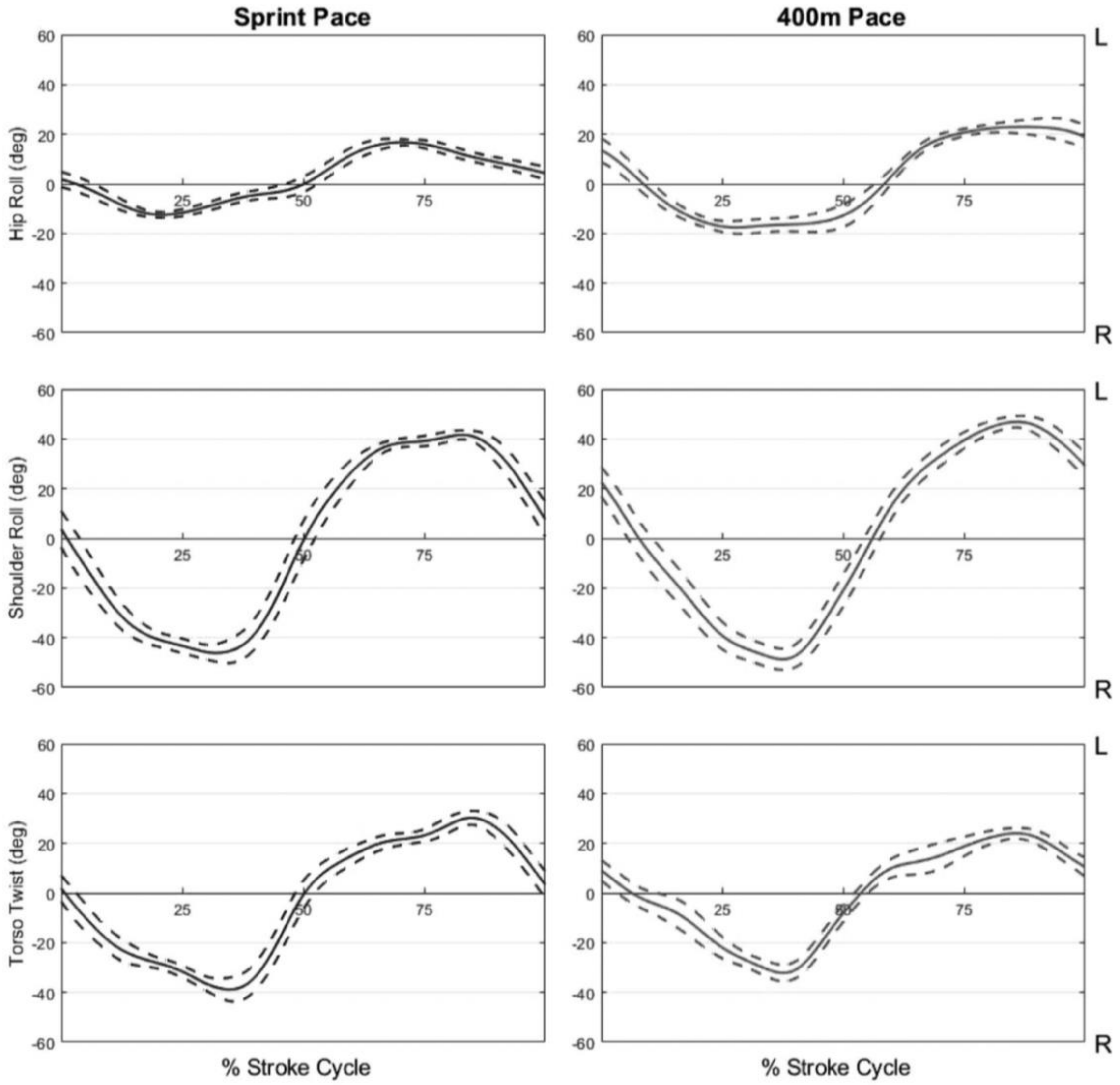


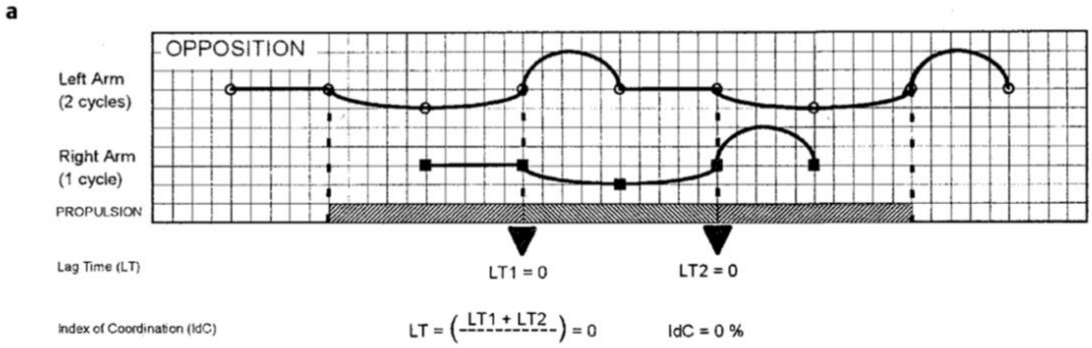
Figure 2.7: Examples of hip roll, shoulder roll, and torso twist at sprint and 400 m front crawl pace for a complete stroke cycle (right hand entry to next right hand entry). Positive values signify swimmer is rotated to their left, and negative values signify they are rotated to their right. Taken from Andersen et al. (2020).

There have been only a couple of studies on body roll in physically impaired swimmers, both focused on unilateral arm amputee front crawl. Using a dynamic CFD model, Lecrivain et al. (2010) demonstrated that, compared to a shoulder roll amplitude of 0^o, a roll amplitude of 45^o increases propulsion generated by the residual limb by 70%. In a later experimental study, (Gonjo et al., 2019) then evidenced that shoulder roll amplitude towards the unaffected side was 19–89% greater than to the affected side for three unilateral arm amputee swimmers. It may be that other Para swimmers with an impairment on one side of the body, for example hemiplegia, might also experience asymmetrical body roll values. Further studies into the effect of impairment severity, health condition and impairment location on body roll are needed to confirm this.

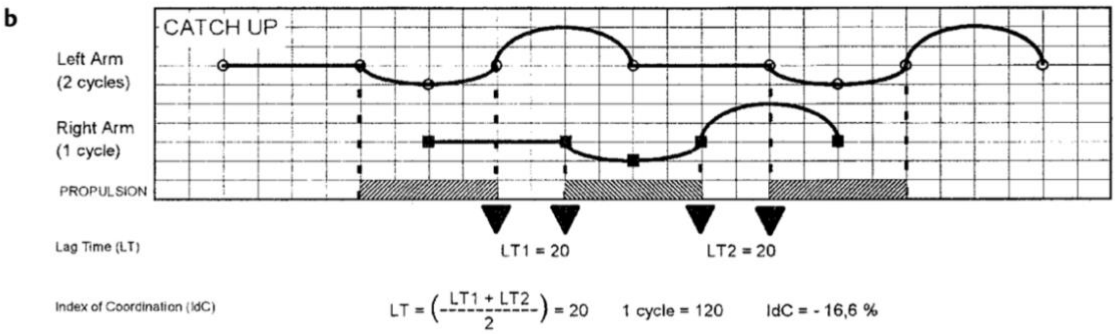
Swimmers with CMNI may have challenges to perform rhythmic and coordinated movements (Hogarth et al., 2019b). It is interesting to note that some CMNI swimmers propel themselves with only their upper limbs due to limited or no function in the lower limbs (Payton et al., 2020). To roll their body in front crawl, swimmers usually use their upper and lower limbs to generate hydrodynamic forces in non-propulsive directions eccentric to the long axis (Yanai, 2001b). However, with limited or absent lower limb function, swimmers with CMNI might not be able to produce the optimum body roll patterns. A front crawl swimmer’s motions affect both the buoyant force and hydrodynamic force acting on their body, creating a interdependence between these forces and the body movements (Yanai, 2004). Scrutinising front crawl movements in swimmers with CMNI could provide some insights into how they roll their body and further establish the effect of impairment type and severity on body roll kinematics.

2.6 Inter-limb coordination

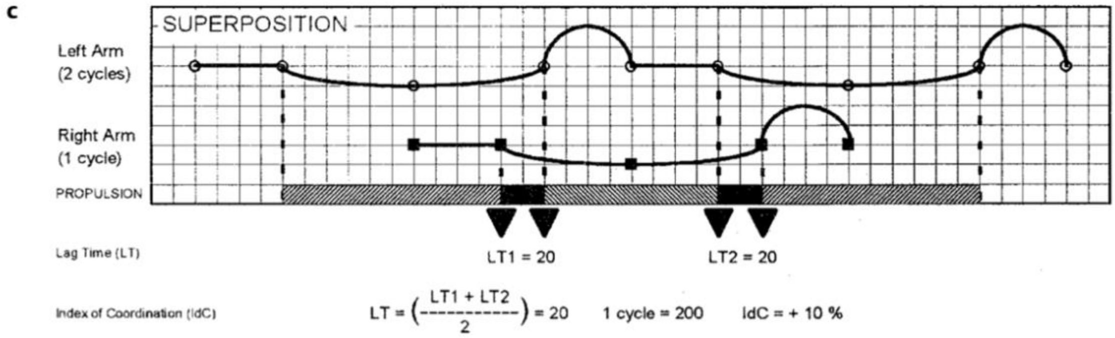
The coordination of the upper limbs in front crawl has been a major area of research in swimming biomechanics for the past few decades. To understand a swimmer’s motor patterns, Chollet and his colleagues (2000) proposed the Index of Coordination (IdC) to quantify the lag time between two propulsive phases of the upper limbs in a stroke cycle. This index has since been adopted widely as the standard method for quantifying the coordination of the upper limbs (Figueiredo et al., 2013b; Gonjo et al., 2020; Ribeiro et al., 2017; Santos et al., 2020a; Seifert et al., 2010c). The IdC identifies three coordination modes in front crawl (Figure 2.8): 1) *catch-up* (when a lag time occurs between two propulsive phases, IdC $<$ 0%), 2) *opposition* (where one upper limb starts its propulsive phase exactly when the other ends its propulsive phase, IdC = 0%), and 3) *superposition* (where an overlap exits between propulsive phases, IdC $>$ 0%).



OPPOSITION : one arm begins the pull phase when the other is finishing the push phase



CATCH UP : a lag time takes place between propulsive phases of the two arms



SUPERPOSITION : an overlap is situated in the propulsive phases

Figure 2.8: Representation of the three models of upper limb coordination in front crawl. Taken from Chollet et al. (2000).

Researchers have investigated the relationship between IdC and front crawl swimming performance and concluded that highly trained swimmers shift their coordination from catch-up mode to superposition mode when their swimming speed increases, while less proficient swimmers maintain a catch-up mode throughout different paces (Chollet et al., 2000; Ribeiro et al., 2017; Schnitzler et al., 2010; Seifert et al., 2007b; Seifert et al., 2010c). This finding provides some evidence that highly trained swimmers achieve better propulsion continuity than less proficient swimmers, indicating that IdC can differentiate between skill levels of swimmers.

One study (Matsuda et al., 2014) appears to contradict the proposed link between skill level and IdC reporting no significant difference between elite and beginner swimmers' IdC when tested at 75–100% of their maximal front crawl speed. This inconsistency with the previous studies' finding (Chollet et al., 2000; Ribeiro et al., 2017; Seifert et al., 2007b) could be explained by two possible reasons: (i) IdC is more sensitive to changes in stroke frequency than it is to differences in skill level (Potdevin et al., 2006; Seifert et al., 2007b). As swimming speed increased, so did stroke frequency and, consequently, the IdC in both skill level groups (Matsuda et al., 2014); and (ii) the difference in the 100 m performance time between the elite and beginner swimmers, 86% and 73% of the world record, respectively, was not substantial. Using the term "sub-elite" could be more suitable than the term "beginner".

In addition to skill level, energy cost is also suggested to be associated with IdC as the coordination of stroke influences the external work done by the swimmer (Figueiredo et al., 2013b; Seifert et al., 2010a). Since IdC is related to stroke frequency (Figueiredo et al., 2013b), and stroke frequency is related to energy cost (Barbosa et al., 2008a), it may be expected that a greater IdC (more overlap of propulsion from upper limbs) would contribute to higher energy cost (Figueiredo et al., 2013b; Seifert et al., 2010a).

Yet Seifert et al. (2014a and 2014b) proposed that individually chosen coordination patterns were the most economical for a swimmer and a high IdC is associated with a low energy cost. Based on the current research, it seems likely there is no single optimal IdC–swimming speed relationship that swimmers should attempt to replicate but rather it involves individualised adaptations (Bideault et al., 2013; Silva et al., 2022) where a personal optimisation of force generation is more accountable for swimming speed (Seifert et al., 2015). This notion of personal optimisation of upper limb coordination in front crawl might be equally applicable to swimmers with a disability who must adapt their arm coordination to compensate for their impairment conditions.

Only a few studies have focused on IdC in physically impaired swimmers. Satkunskienė et al. (2005) found no relationship between IdC (-25% to +29%) and sport class in 18 CMNI swimmers from classes S3–S10, however, more skilled swimmers (defined by their 100 m race speed relative to the class world record) utilised greater IdC compared to their less skilled counterparts. The high inter-swimmer variability in IdC values could be due to different strategies to maintain balance as not all of their limbs contributed to propulsion (Satkunskienė et al., 2005). Another study of 11 Para swimmers with various physical impairments (S5–S10) reported a mean IdC value of – 11% and observed that higher stroke frequencies led to a higher IdC (Feitosa et al., 2019). Compared to non-disabled swimmers (mean IdC of 0%), a group of 20 Para swimmers (S5–S10) used more catch-up mode (mean IdC of -2%) and exhibited greater asymmetry in their coordination during maximal speed front crawl (Santos et al., 2020b; Santos et al., 2020a). These three recent studies (Feitosa et al., 2019; Santos et al., 2020b; Santos et al., 2020a) grouped all physical impairment types together and did not attempt to explore the impacts of impairment type and impairment severity on IdC. Thus, the relationship between impairment types and IdC remains unknown in CMNI population. Future research is needed to address these areas. This information could help inform the classification of swimmers with CMNI in a revised evidence-based system.

Although IdC purports to quantify the time gap between upper limb propulsion, the index does not address many aspects of motor coordination in swimming. Motor coordination has been defined as the ability to move fluidly, rapidly and accurately (Connick et al., 2016). From this definition, IdC does not quantify any component of motor coordination, rather it just establishes the timing between the two upper limbs. Silva et al. (2022) acknowledged that IdC is not the best measurement for coordination because it only presents temporal information on coordinating propulsive phases.

2.7 Intra-cyclic speed fluctuation

In a front crawl stroke cycle swimmers do not move forward at a constant speed (Seifert et al., 2015). The profile of intra-cyclic speed fluctuation (ICSF) represents the positive and negative accelerations of the centre of mass of the body (Fernandes et al., 2012). Intra-cyclic speed fluctuation is widely presented as an indicator of swimming efficiency (Alberty et al., 2005; Alves, 1996; Barbosa et al., 2006; Barbosa et al., 2013b; Nigg, 1983; Vilas-Boas, 2005, 2010) as the speed curve represents a swimmer’s ability to coordinate the propulsive forces while minimising resistive forces within a stroke cycle (Alberty et al., 2005; Matsuda et al., 2014; Silva et al., 2019). Intra-cyclic speed fluctuation is higher in simultaneous movements (breaststroke and butterfly) than in alternated movements (backstroke and front crawl) owing to the mechanical impulses acting on a swimmer (Barbosa et al., 2017; Barbosa et al., 2013b; Bartolomeu et al., 2018). In addition, females generally present lower intra-cyclic speed fluctuation than males, as sex differences in anthropometrics and mechanical power output result in females having less drag force to overcome (Barbosa et al., 2013a; Manley and Atha, 2013; Schnitzler et al., 2008).

Intra-cyclic speed fluctuation is calculated using speed-time series data obtained from either a fixed point on the swimmer's body, commonly the hip (Alberty et al., 2005; Schnitzler et al., 2010) or from 3D reconstruction of the swimmer's centre of mass (Gourgoulis et al., 2018; Psycharakis and Sanders, 2009). The majority of studies have used the fixed point approach due to the simplicity of collecting the required data. Locating the centre of mass using 3D motion analysis is relatively time-consuming and its accuracy depends on the inertia data used (Schnitzler et al., 2010). However, it is apparent that tracking of the hip, or other fixed location on the swimmer, does not accurately capture the intra-cyclic variations of the centre of mass speed (Gourgoulis et al., 2018) and may compromise the validity of the measurements. Several limitations of using a fixed point to represent centre of mass kinematics have been reported. Swimming involves multi-segment, three-dimensional movement so reducing this to the two-dimensional motion of a single point might not be appropriate to estimate intra-cyclic speed fluctuation. In front crawl, swimmers undertake a continuous hip roll movement throughout the stroke cycle. Displacement of a fixed point on the trunk does not reflect movement of the actual centre of mass because the relative motions of the other body segments, such as the recovery of the upper limbs over the water, are not accounted for (Gourgoulis et al., 2018; Maglischo et al., 1987). Errors linked to the single-point approach for estimating the centre of mass mean forward velocity and horizontal displacement are 7.5% and 3.2%, respectively (Figure 2.9) (Fernandes et al., 2012). The single-point approach also overestimates the intra-cyclic speed range by 49–95% (Gourgoulis et al., 2018; Psycharakis and Sanders, 2009). Measuring the swimmer's mass centre kinematics from three-dimensional motion analysis, accordingly, is advocated as the most accurate and valid method to assess intra-cyclic speed fluctuation (Figueiredo et al., 2009; Gourgoulis et al., 2018; Psycharakis et al., 2010).

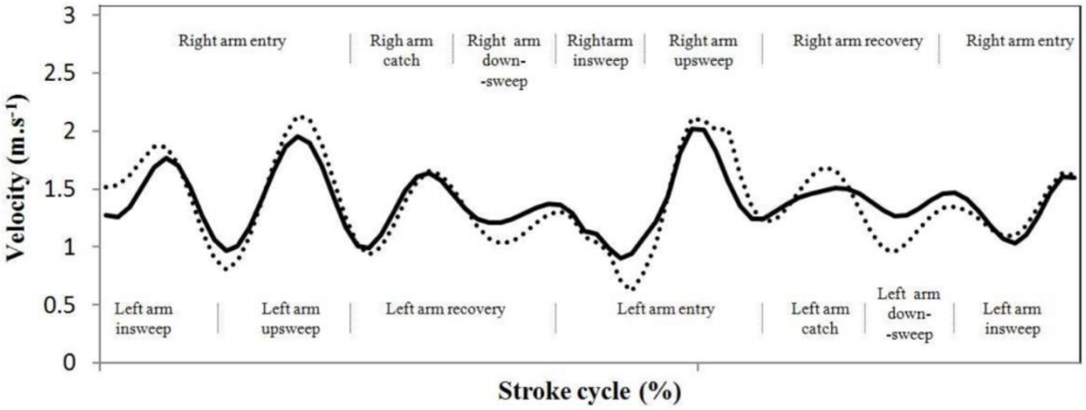


Figure 2.9: Example of the intra-cyclic speed fluctuations of the hip (dashed line) and of the centre of mass (continuous line) for one front crawl swimmer. Taken from Fernandes et al. (2012).

Researchers have calculated intra-cyclic speed fluctuation in two ways. The coefficient of variation ($ICSF_{CV}$) is a widely used parameter (Barbosa et al., 2006; Fernandes et al., 2012; Matsuda et al., 2014; Schnitzler et al., 2010) that represents the ratio of the standard deviation to the mean [(standard deviation/mean)*100]. It is computed as follows:

$$ICSF_{CV} = \frac{\sqrt{\Sigma_i (v_i - \bar{v}) 2 F_i / n}}{\Sigma_i v_i \, F_i / n} \, 100 \qquad [2.15]$$

Where: v represents mean swimming speed, v_i instant swimming speed, F_i absolute frequency and n is the number of observations. Alternatively, an $ICSF_{\%}$ can be calculated by dividing the range of the swimming speed within the stroke cycle by the mean swimming speed for the stroke cycle (Payton and Wilcox, 2006; Psycharakis et al., 2010).

Non-disabled swimmers show intra-cyclic speed fluctuation values ranging from 6–24% in front crawl when both calculation methods are considered (Alberty et al., 2005; Craig and Pendergast, 1979; Fernandes et al., 2022; Gonjo et al., 2018; Matsuda et al., 2014; Psycharakis et al., 2010; Schnitzler et al., 2010; Seifert et al., 2010c). Gonjo et al. (2019) recently highlighted some limitations with current ways of expressing intra-cyclic speed fluctuation, stating that $ICSF_{\%}$ highlights maximum swimming speed amplitude but does not represent the overall speed fluctuation within a stroke cycle. In contrast, while $ICSF_{CV}$ does reflect overall speed fluctuation variability, the amplitude of swimming speed is not shown. It should be noted that at present, no method is considered better than the other, rather they each present different aspects of the speed curve (O'Dowd et al., 2023). As different data capture and calculation procedures are used in intra-cyclic speed fluctuation assessment, care should be taken when comparing findings and conclusions between studies.

The relationship between intra-cyclic speed fluctuation, swimming speed and performance in non-disabled swimmers is controversial in front crawl. Some studies report no relationship between these factors (Fernandes et al., 2022; Psycharakis et al., 2010; Seifert et al., 2008), whilst others have found that increased swimming speed links to lower (Barbosa et al., 2013b), stable (Alberty et al., 2005; Dadashi et al., 2016; De Jesus et al., 2016; Figueiredo et al., 2013b; Matsuda et al., 2014; Schnitzler et al., 2010; Schnitzler et al., 2008), or increased speed fluctuation up to a point, after which it decreases (Barbosa et al., 2006). Additionally, when assessing performance levels, faster swimmers were found to exhibit higher (Barbosa et al., 2021), lower (Alves, 1996; Barbosa et al., 2006; Matsuda et al., 2014; Schnitzler et al., 2008; Silva et al., 2019), or similar intra-cyclic speed fluctuation (Fernandes et al., 2022) compared to slower swimmers. Other than differences in data collection and analysis methods used, the discrepancies between these aforementioned studies may be partially explained by sex differences, stroke specialism, swimmer skill level, and event distance.

It is typically recommended that swimmers should minimise or maintain intra-cyclic speed fluctuation in order to be more economical in front crawl (Arellano et al., 2010; Barbosa et al., 2008b; Fernandes et al., 2023; Schnitzler et al., 2010; Seifert et al., 2014b). This is because greater fluctuations in swimming speed lead to an increase in the work required from the swimmer to overcome inertia and drag (Nigg, 1983). When a swimmer accelerates and decelerates their body, greater energy expenditure is required (Gonjo et al., 2018; Vilas-Boas et al., 2011). As such, speed fluctuation is associated with the energy cost of swimming (Barbosa et al., 2010; Gonjo et al., 2018; Zamparo et al., 2020). The relationship between intra-cyclic speed fluctuation and IdC has also been examined. Swimmers are able to maintain their intra-cyclic speed fluctuation while increasing their IdC during a maximal effort 200 m front crawl swim (Alberty et al., 2005; Barbosa et al., 2005; Figueiredo et al., 2013a) or at different swimming paces (Alves, 1996; Matsuda et al., 2014; Schnitzler et al., 2008), indicating that speed fluctuation and IdC are not interdependent. Silva et al. (2022) explained this might be related to IdC not reflecting the magnitudes of propulsive and resistive forces but only showing the temporal continuity between the upper limbs. As such, the relationship between intra-cyclic speed fluctuation and upper limb coordination remains unclear. It can only be said that timing of the upper limbs does not influence intra-cyclic speed fluctuation in front crawl swimming.

Research on intra-cyclic speed fluctuation in physically impaired swimmers is limited. Two studies have used intra-cyclic speed fluctuation to determine how effectively propulsion is generated by the stump of unilateral arm amputee swimmers (O'Dowd et al., 2023; Payton and Wilcox, 2006). Both concluded that swimming speed decreases during the propulsive phases (pull and push) of the stump and increases during the propulsive phases of the unaffected upper limb. In a study of nine male Para swimmers with various impairment types, S6–S9, Junior et al. (2018) concluded that a decrease in speed fluctuation was observed with an increase in swimming speed and stroke frequency, indicating that intra-cyclic speed fluctuation directly impacts swimming performance. Conversely, using hip displacement to assess speed fluctuation, Santos et al. (2020a) concluded that intra-cyclic speed fluctuation does not predict swimming performance as speed fluctuation did not differ between elite and sub-elite non-disabled groups and between non-disabled and a group of physically impaired swimmers (S5–S10). Both studies used three-dimensional motion analysis although one did not specify their procedure for calculating speed fluctuation (Junior et al., 2018). Both studies did not specify the number of swimmers with certain type of physical impairment that were examined, nor did they try to establish the relationship between intra-cyclic speed fluctuation and impairment type and impairment severity.

In contrast, Feitosa et al. (2019) were the first to attempt to explain the relationship between intra-cyclic speed fluctuation and physical impairment (7 limb deficiency; 4 CMNI; S5–S10) in front crawl swimming. Using three-dimensional motion analysis, they reported higher intra-cyclic speed fluctuation and lower Froude efficiency in the lower sport classes (more impaired). This finding provides some indirect evidence that swimmers with more severe impairments may expend more energy to achieve the same swimming task than less impaired swimmers, with their intra-cyclic speed fluctuation values ranging from 14–36%. Unfortunately, due to the small number of CMNI swimmers in this study, the researchers were only able to provide case-by-case interpretations of the link between impairment type and performance. Thus, the relationship between intra-cyclic speed fluctuation and swimming performance in CMNI swimmers remains unclear. As CMNI swimmers present different techniques in front crawl depending on their impairment type, future studies should consider investigating intra-cyclic speed fluctuation in different technique groups (e.g., with and without lower limb function).

2.8 Summary

Due to the nature of CMNI, a group of these swimmers will have a much more diverse range of movement patterns compared to non-disabled swimmers when swimming freestyle. To develop sport-specific measures of performance determinants for this population (Tweedy et al., 2016), it is necessary to measure their front crawl performance-related biomechanical variables in the water. There is presently only a small body of scientific literature on biomechanical characteristics of highly trained front crawl swimmers with CMNI. Most studies have investigated Para swimmers with various impairment types, with an unspecified number of CMNI participants, rather than focusing on one impairment group. The following areas in front crawl swimmers with CMNI have been explored (Table 2.1).

Table 2.1: Research studies undertaken on swimmers with central motor and neuromuscular impairment in front crawl.

Research area	Study	Para swimmers	CMNI swimmers	Sport class
Stroking parameters	Feitosa et al. (2019)	n = 11	n = 4	S5–S8
	Santos et al. (2020a)	n = 20	unknown	S5–S10
Index of Coordination	Santos et al. (2020a)	n = 20	unknown	S5–S10
	Santos et al. (2020b)	n = 20	unknown	S5–S10
	Feitosa et al. (2019)	n = 11	n = 4	S5–S8
	Satkunskienė et al. (2005)	n = 0	n = 18	S3–S10
Hand trajectories	Santos et al. (2020a)	n = 20	unknown	S5–S10
	Santos et al. (2020b)	n = 20	unknown	S5–S10
Intra-cyclic speed fluctuation	Feitosa et al. (2019)	n = 11	n = 4	S5–S8
	Santos et al. (2020a)	n = 20	unknown	S5–S10
Froude efficiency	Feitosa et al. (2019)	n = 11	n = 4	S5–S8
Active drag	Payton et al. (2020)	n = 72	n = 36	S1–S9
Passive drag	Hogarth et al. (2021)	n = 132	n = 64	S1–S10
	Oh et al. (2013)	n = 113	unknown	S3–S14
Tethered force production	Hogarth et al. (2020)	n = 80	n = 41	S1–S10

This review has highlighted that only a limited body of knowledge exists for CMNI front crawl performance. This thesis will address this issue by comparing the biomechanical variables of non-disabled and CMNI freestyle swimmers. In addition, the impact of CMNI severity, health condition and impairment location on front crawl biomechanics will be examined. The findings from this thesis will contribute to the body of knowledge surrounding CMNI front crawl performance and as such, the development of a new evidence-based classification system for Para swimming. Ultimately, this will enable Para swimmers to compete in a more fair and equitable manner.

2.9 Academic aims

The academic aim of this thesis is to improve our understanding of how central motor and neuromuscular impairment influences freestyle swimming technique and the impact that this has on performance. The thesis focusses on two main areas: First, the biomechanical characteristics of the freestyle techniques employed by CMNI swimmers and the biomechanical variables which are associated with freestyle performance. Second, how kinematic variables potentially influence propulsion generation and drag reduction in freestyle.

This thesis has five objectives which are to:

(i) characterise the stroke parameters adopted by highly trained swimmers with central motor and neuromuscular impairment during sprint and paced freestyle race performances (study 1);

(ii) establish the differences in upper limb, lower limb and trunk kinematics between highly trained central motor and neuromuscular impaired swimmers and non-disabled front crawl swimmers (studies 2 and 3);

(iii) determine the influence of central motor and neuromuscular impairment severity and impairment location on biomechanical determinants of front crawl performance (studies 2 and 3);

(iv) establish the differences in intra-cyclic speed fluctuation, index of coordination, and Froude efficiency between highly trained central motor and neuromuscular impaired swimmers and non-disabled front crawl swimmers (study 4);

(v) determine the influence of central motor and neuromuscular impairment severity on intra-cyclic speed fluctuation, index of coordination, and Froude efficiency of front crawl performance (study 4);

(vi) describe the kinematics of double-arm backstroke, a specialist freestyle technique, and then determine how severe central motor and neuromuscular impairment limits performance of this technique (study 5).

CHAPTER 3

Study 1: Freestyle stroke parameters in highly trained swimmers with central motor and neuromuscular impairment

3.1 INTRODUCTION

Swimming is a form of locomotion which requires the action of hydrodynamic forces on the body to move the swimmer forward in the water. Swimming performance time in a race primarily depends on the swimmer's speed which is the product of two stroke parameters: Stroke Length and Stroke Frequency (Craig and Pendergast, 1979; Morais et al., 2022):

$$\text{Swimming Speed} = \text{Stroke Length} \times \text{Stroke Frequency} \qquad [3.1]$$

In non-disabled swimming, it is well-documented that faster swimmers are able to achieve greater distance per stroke (stroke length) in races, suggesting that they have superior techniques to generate better propulsion, compared to slower swimmers (Morais et al., 2022).

Stroke parameters of freestyle performance have previously been explored in Para swimming. Pelayo et al. (1999) and Daly and Vanlandewijck (1999) both reported that Para swimmers use a greater range of stroke frequency and stroke length combinations to achieve the same speed as Olympic swimmers do. Due to the variety of physical impairment types, these swimmers may demonstrate tactical movement patterns to compensate for their disability. Lower class swimmers, for instance, might adopt increasing stroke frequency to obtain maximal swimming speed (Junior et al., 2018; Santos et al., 2020a; Satkunskienė et al., 2005). However, swimming speed was found to be influenced more by stroke length than by stroke frequency in physically impaired swimmers when sprinting, with shorter stroke length associated with more impaired swimmers (Daly and Vanlandewijck, 1999; Feitosa et al., 2019; Pelayo et al., 1999; Santos et al., 2020a; Satkunskienė et al., 2005).

The current method of classifying physically impaired swimmers uses a functional classification system to group athletes for fair competition. However, the validity of the classification system is questionable because the process relies on the subjective opinion of clinical experts who score a swimmer's activity limitation using ordinal scale measures. In 2009, the International Paralympic Committee mandated the development of new evidence-based classification systems in Para sport (Tweedy and Vanlandewijck, 2011). Previous studies have highlighted important limitations of the current functional classification system (Burkett et al., 2018; Daly and Vanlandewijck, 1999; Oh et al., 2013; Santos et al., 2019; Wu and Williams, 1999). That is, certain impairment types are disadvantaged due to different impairment conditions competing within a single class.

Swimmers with central motor and neuromuscular impairment (CMNI) are challenging to classify objectively in Para swimming because many of the quantitative measurements required for evidence-based classification are yet to be explored (Tweedy et al., 2016). Motor coordination is an ability to activate multiple joints and muscles to execute accurate, smooth and efficient movement (Shumway-Cook and Woollacott, 2014). Individuals with CMNI are defined as having an underlying health condition of traumatic brain injury, cerebral palsy, spinal cord injury or other neuromuscular disorder that might cause awkward, extraneous, uneven, or inaccurate movement characteristics (Schmitz and O'sullivan, 2013). The activity limitations that this population exhibit can vary considerably according to the type, the severity, or the location of the pathology.

CMNI has been shown to adversely affect movements in land-based sports; these effects include impaired range of motion (ROM) (Connick et al., 2015), reduced body strength (Beckman et al., 2016) and poor motor coordination (Roldán et al., 2017). It can be speculated therefore, that swimmers with these health conditions may be similarly affected in water. Despite this, CMNI swimmers are not always classified using the complete battery of classification tests currently available (strength, ROM, and coordination), even if their health condition demonstrates a combination of all these limitations. In fact, Hogarth et al. (2019b) revealed that although individuals with hypertonia exhibit strength impairment in their swimming performance, most Para swimmers with this condition are classified based on the coordination test alone. Furthermore, hypertonia often causes a degree of spasticity which might also constrain swimming performance by reducing ROM and motor coordination. Thus, the severity of CMNI might be underestimated during classification and further disadvantage this population within their swimming-specific impairment class.

A greater understanding of how CMNI influences swimming movement based on impairment severity and health condition will be informative when classifying these athletes and ultimately achieve fair competition. The majority of previous studies that have examined physically impaired swimmers have treated them as one collective group, despite a broad range of impairment types (Daly and Vanlandewijck, 1999; Dingley et al., 2014; Junior et al., 2018; Pelayo et al., 1999; Santos et al., 2019; Santos et al., 2020a). Swimmers with CMNI are rarely examined as one specific population to investigate the impact of impairment severity and health condition on swimming performance, other than in these five studies (Feitosa et al., 2019; Payton et al., 2020; Santos et al., 2020a; Santos et al., 2017; Satkunskienė et al., 2005). As such, very little is known about how CMNI influences a swimmer’s movement in the water. The aim of this study was to establish the impact of CMNI severity and health condition on freestyle stroke parameters during competition. Previous research has established that stroke length is a more important factor than stroke frequency to swimming speed in non-disabled swimmers. Yet this has not been explored specifically in CMNI swimmers. The hypotheses are that: (i) stroke length, rather than stroke frequency, is the limiting factor to performance in swimmers with CMNI, and (ii) more impaired CMNI swimmers present shorter stroke length than less impaired CMNI swimmers during freestyle swimming.

3.2 METHODS

3.2.1 Participants and data sources

The freestyle stroke data in this study were sourced from a London Paralympic Games 2012 performance analysis project and from Great Britain Para swimming's NEMO database (n = 223, S2–S10; Table 3.1). Data from the London Paralympic Games 2012 were for final races only; data from the NEMO database were for the best performances that each GB swimmer achieved at any long course swimming event between 2015 and 2022. The London Project was led by this PhD's Principal Supervisor. To access to the NEMO database, the Performance Director had permitted the authors to generate some of the data. Inclusion criteria were an international swimming classification and an eligible impairment type, such as impaired muscle power, hypertonia, ataxia and athetosis, resulting from acquired or congenital brain injury, neuromuscular disorder or spinal cord injury. In this study, sport class is adopted as an indirect measure of swimming-specific impairment severity. Despite criticisms of its objectivity, the sport class It is currently derived from the best available practice (Tweedy and Vanlandewijck, 2011) and its allocation is based on the impact of impairment on swimming, rather than on the impairment itself (World Para Swimming, 2018).

Table 3.1: Characteristics of freestyle swims for Para swimmers with CMNI from sport classes S2–S10 (n = 223; male = 110; female = 113) from London Paralympic Games 2012 and the Great Britain Para swimming NEMO database (2015–2022).

	S10		S9		S8		S7		S6		S5		S4		S3		S2	
	M (n=13)	**F (n=20)**	**M (n=13)**	**F (n=1)**	**M (n=15)**	**F (n=14)**	**M (n=24)**	**F (n=32)**	**M (n=10)**	**F (n=17)**	**M (n=5)**	**F (n=15)**	**M (n=14)**	**F (n=2)**	**M (n=0)**	**F (n=12)**	**M (n=16)**	**F (n=0)**
Freestyle events																		
50 m (n=80)	4	5	4	-	6	8	7	11	3	7	2	4	4	1	-	6	8	-
100 m (n=85)	5	6	5	-	6	5	9	11	5	6	2	6	5	-	-	6	8	-
200 m (n=15)	-	1	-	-	-	-	1	1	-	-	1	5	5	1	-	-	-	-
400 m (n=43)	4	8	4	1	3	1	7	9	2	4	-	-	-	-	-	-	-	-
Health condition																		
Brain injury (n=134)	9	14	8	-	11	9	22	27	4	7	2	2	5	-	-	7	7	-
Neuromuscular disorder (n=33)	4	3	3	1	4	4	1	-	-	-	-	3	2	2	-	3	3	-
Spinal cord injury (n=56)	-	3	2	-	-	1	1	5	6	10	3	10	7	-	-	2	6	-
Freestyle variations																		
Front crawl with bilateral kick (n=39)	5	11	6	1	6	5	2	-	-	1	-	2	-	-	-	-	-	-
Front crawl with unilateral kick (n=65)	5	9	6	-	5	8	10	11	3	6	2	-	-	-	-	-	-	-
Front crawl without kick (n=100)	3	-	1	-	4	1	12	21	7	10	3	13	14	2	-	6	3	-
Backstroke without kick (n=11)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	6	-
Double-arm backstroke without kick (n=8)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	7	-

3.2.2 Pool calibration and data capture

The men's and women's 50 m, 100 m, 200 m and 400 m freestyle swims in this study were all recorded using 50 Hz video cameras. Prior to the start of the competition, black markers (tape) were placed on each side of the 50 m pool at 5 m, 15 m, 25 m, 40 m and 45 m from the start end. Distances were measured using a laser measure with a resolution of ± 1.5 mm (Leica Camera AG, Germany). Lane ropes were then aligned and clamped to limit movement of the plastic discs on the lane ropes. Five digital photographs of the markers and lane ropes were then used to produce a composite image to enable accurate identification of distances during analysis (Figure 3.1). Performance (race) times and splits for each 50 m were obtained from the official timing system at the competition.

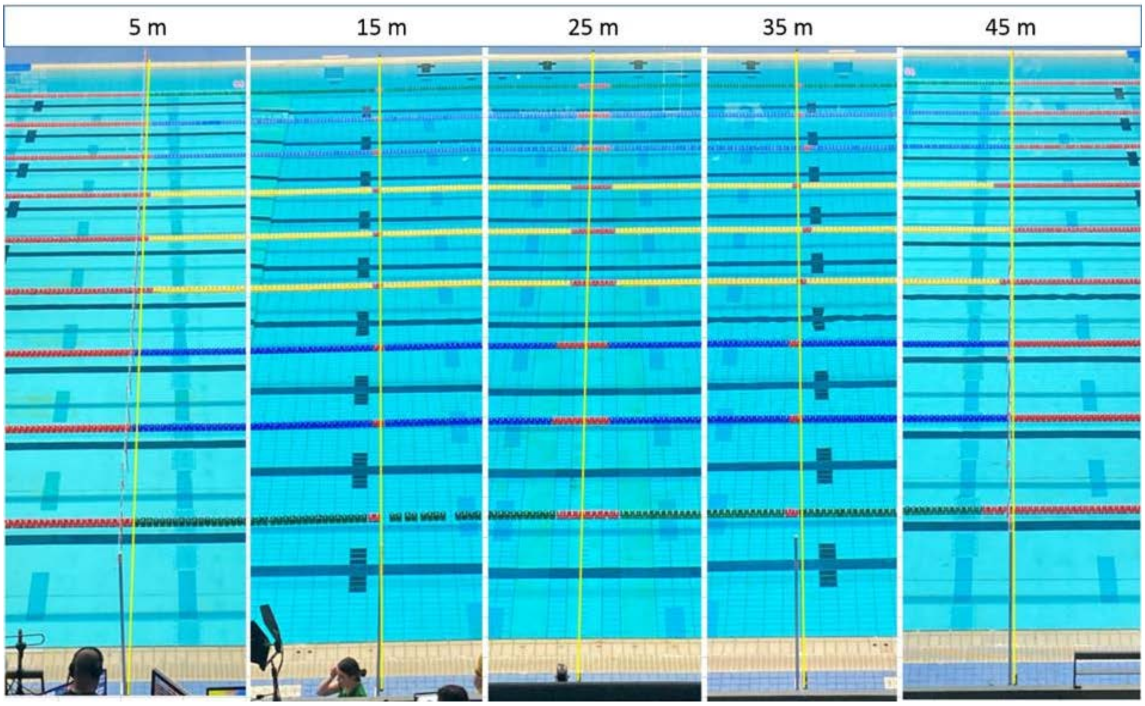


Figure 3.1: Pool calibration image showing lines drawn at key distances.

3.2.3 Data processing and analysis

The videos were imported into NEMO, a bespoke race analysis software developed exclusively for British Swimming. The following variables were measured: mean swimming speed, stroke frequency and stroke length during each length of the race. Data were categorised based on sport class (S2–S10), health condition and freestyle variations. The time of each upper limb stroke cycle was manually recorded in NEMO software by tagging every water entry of the same hand on one side of the body only. The side that was tagged for each length was the first hand to enter the water following exit from the underwater start phase. The half stroke at the beginning of each length was accounted for by tagging the final full stroke of each length as a half stroke. The time for the front of the swimmer's head to reach 5 m, 15 m, 25 m and 45 m was tagged for every length. A mean stroke frequency (stroke·min^{-1}) was calculated over the whole race using the following equation:

Stroke Frequency = [No. of stroke cycles/time to complete the stroke cycles] × 60 [3.2]

Swimming Speed (m·s^{-1}) was calculated as:

$$\text{Swimming Speed} = \text{distance} / \text{time} \qquad [3.3]$$

Where distance is the total clean swim distance, and the time is the time to complete.

Mean Stroke Length (m) was calculated as:

Stroke Length = mean swimming speed / mean stroke frequency *60 [3.4]

The four freestyle distance events were grouped into sprint swims (50 m and 100 m) and paced swims (200 m and 400 m). Data are presented for the pooled CMNI group and then CMNI swimmers were categorised separately into: (i) three health conditions: brain injury, neuromuscular disorder and spinal cord injury, (ii) nine sport classes to represent their swimming-specific impairment severity and (iii) five freestyle variations depending on their activity limitation when completing the freestyle stroke: front crawl with bilateral kick, front crawl with unilateral kick, front crawl without kick, backstroke without kick and double-arm backstroke without kick. Male and female participants were pooled together for analysis since the aim of this study was to investigate the effect of impairment on freestyle. The trends of association between variables were expected to be the same despite biological sex.

3.2.4 Statistical analysis

IBM SPSS Statistics 28 was used to analyse the data. All data were checked for parametricity. The effects of impairment severity (sport class) on swimming speed, stroke frequency and stroke length were determined using Kendall's tau coefficient. Strength of associations were interpreted such that ≤ .40 = small, .41 to .60 = moderate, .61 to .79 = large and ≥ .80 = very large (Mukaka, 2012). The mean and standard deviation (SD) of swimming speed, stroke frequency and stroke length were described for each freestyle variation and health condition in sprint and paced swims. Kruskal-Wallis H tests were used to establish differences in swimming speed, stroke frequency and stroke length between freestyle variations for the pooled CMNI group and between the three impairment groups within each freestyle variation for sprint and paced swims. It was not feasible to statistically analyse the difference between subgroups when the sample size was less than 5. Multiple comparisons were made using Bonferroni corrected post hoc pairwise comparisons. To assess the effects of stroke frequency and stroke length on swimming performance, Pearson correlation coefficient was used to calculate the strength of relationships among stroke parameters. The threshold for statistical significance was set at $p < .05$.

3.3 RESULTS

3.3.1 Sprint swims (50 m & 100 m)

Effect of impairment severity

Figure 3.2 shows that for the CMNI swimmers collectively and for each sub-group, sport class had significant positive associations with swimming speed and stroke length (τ = .47 to .75, *p* < .001). Although a small positive association was found between stroke frequency and sport class in CMNI swimmers collectively (τ = .12, *p* < .05), no association between these variables was found when CMNI swimmers were sub-grouped into brain injury and neuromuscular disorder groups (*p* > .05). For the spinal cord injury group however, sport class was moderately associated with stroke frequency values (τ = .42, *p* < .001).

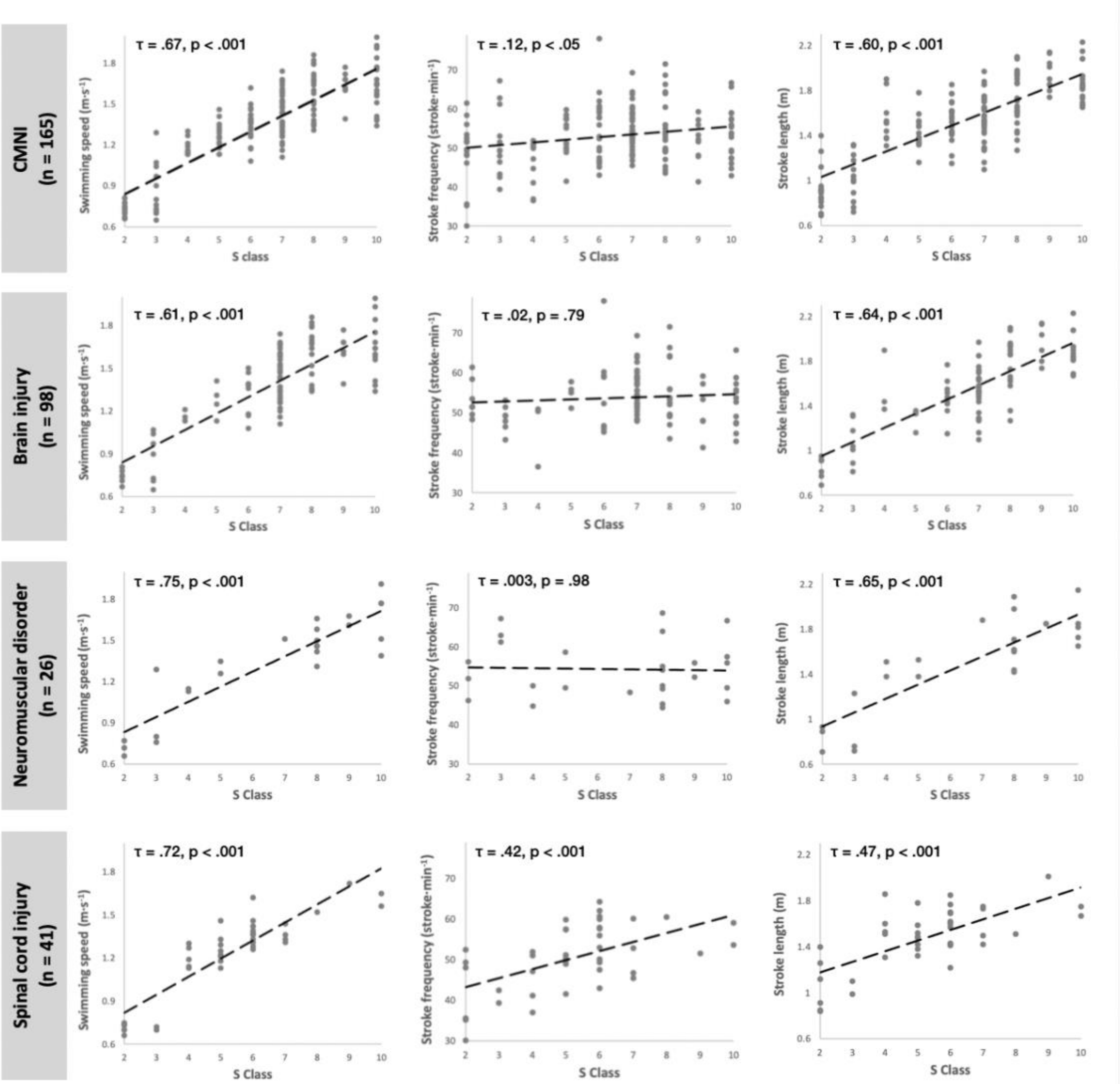


Figure 3.2: Scatterplots of swimming speed, stroke frequency and stroke length versus physical impairment sport class (S2–S10), presented as a pooled CMNI group (n = 165) and then sub-grouped into brain injury (n = 98), neuromuscular disorder (n = 26) and spinal cord injury (n = 41) in sprint freestyle swims (50 m & 100 m).

Effect of freestyle variations and health condition

There was a significant difference in CMNI swimming speed ($X^2(4) = 66.902$, $p < .001$) and stroke length ($X^2(4) = 60.052$, $p < .001$) between freestyle variations (Table 3.2). The closer the freestyle variation was to typical front crawl technique, the faster swimming speed and greater stroke length values swimmers exhibited. Stroke frequency did not differ between freestyle variations ($p > .05$). Post hoc tests revealed that swimming speed was statistically different amongst all freestyle variations ($p < .05$) other than between front crawl with bilateral and uniliteral kick and between backstroke and double-arm backstroke ($p > .05$). Likewise, stroke length differed between freestyle variations ($p < .05$) except for between front crawl with bilateral and uniliteral kick, between front crawl with unilateral kick and without kick and between backstroke and double-arm backstroke ($p > .05$). No significant difference in swimming speed, stroke frequency or stroke length was found between the three health conditions for any of the freestyle variations ($p > .05$).

Table 3.2: Swimming speed, stroke frequency and stroke length (mean ± SD) for five freestyle variations, presented as a pooled CMNI group and for each sub-group of brain injury, neuromuscular disorder, and spinal cord injury during sprint freestyle swims (50 m & 100 m; n = 165). Differences were shown as ^{a} from front crawl with bilateral kick; ^{b} from front crawl with unilateral kick; ^{c} from front crawl without kick; ^{d} from backstroke without kick; ^{e} from double-arm backstroke without kick; * from brain injury; $^{\#}$ from neuromuscular disorder; and § from spinal cord injury.

Freestyle variations	Swimming speed ($m{\cdot}s^{-1}$)	Stroke frequency ($stroke{\cdot}min^{-1}$)	Stroke length (m)
Front crawl with bilateral kick			
CMNI (n=26)	1.54 ± 0.20 ^{cde}	52.8 ± 6.2	1.76 ± 0.21 ^{cde}
Brain injury (n=13)	1.48 ± 0.22	52.5 ± 6.3	1.70 ± 0.24
Neuromuscular disorder (n=11)	1.60 ± 0.17	52.6 ± 6.6	1.85 ± 0.17
Spinal cord injury (n=2)	1.56 – 1.65	53.6 – 59.1	1.67 – 1.75
Front crawl with unilateral kick			
CMNI (n=48)	1.51 ± 0.20 ^{cde}	55.0 ± 7.3	1.67 ± 0.27 ^{de}
Brain injury (n=44)	1.51 ± 0.21	54.7 ± 7.2	1.68 ± 0.27
Neuromuscular disorder (n=4)	1.48 ± 0.14	59.0 ± 8.9	1.52 ± 0.11
Spinal cord injury (n=0)	-	-	-
Front crawl without kick			
CMNI (n=72)	1.32 ± 0.25 ^{abde}	52.9 ± 7.1	1.51 ± 0.28 ^{ade}
Brain injury (n=34)	1.32 ± 0.32	54.1 ± 6.8	1.47 ± 0.35
Neuromuscular disorder (n=6)	1.28 ± 0.14	52.4 ± 6.9	1.48 ± 0.22
Spinal cord injury (n=32)	1.31 ± 0.18	51.8 ± 7.4	1.55 ± 0.19
Backstroke without kick			
CMNI (n=11)	0.77 ± 0.10 ^{abc}	49.7 ± 10.1	0.97 ± 0.20 ^{abc}
Brain injury (n=4)	0.83 ± 0.15	52.0 ± 1.7	0.96 ± 0.16
Neuromuscular disorder (n=4)	0.76 ± 0.03	56.6 ± 9.4	0.83 ± 0.10
Spinal cord injury (n=3)	0.71 ± 0.01	37.3 ± 6.5	1.16 ± 0.21
Double-arm backstroke without kick			
CMNI (n=8)	0.72 ± 0.05 ^{abc}	48.7 ± 6.0	0.90 ± 0.16 ^{abc}
Brain injury (n=3)	0.72 ± 0.07	49.3 ± 1.9	0.88 ± 0.06
Neuromuscular disorder (n=1)	0.66	56.1	0.71
Spinal cord injury (n=4)	0.73 ± 0.02	46.4 ± 7.4	0.97 ± 0.20

Relationships between swimming speed, stroke frequency and stroke length

Small positive associations were found between stroke frequency and swimming speed in CMNI swimmers collectively (*r* = .38, *p* < .001) and brain injury sub-group (*r* = .31, *p* < .01; Figure 3.3). In the spinal cord injury sub-group, stroke frequency had a large positive association with swimming speed (*r* = .64, *p* < .001). Large to very large positive associations were found between stroke length and swimming speed in CMNI swimmers collectively and in all sub-groups (*r* = .79 to .88, *p* < .001). Small negative associations were found between stroke length and stroke frequency in CMNI swimmers collectively and in brain injury and neuromuscular disorder sub-groups (*r* = - .29 to - .17, *p* < .05).

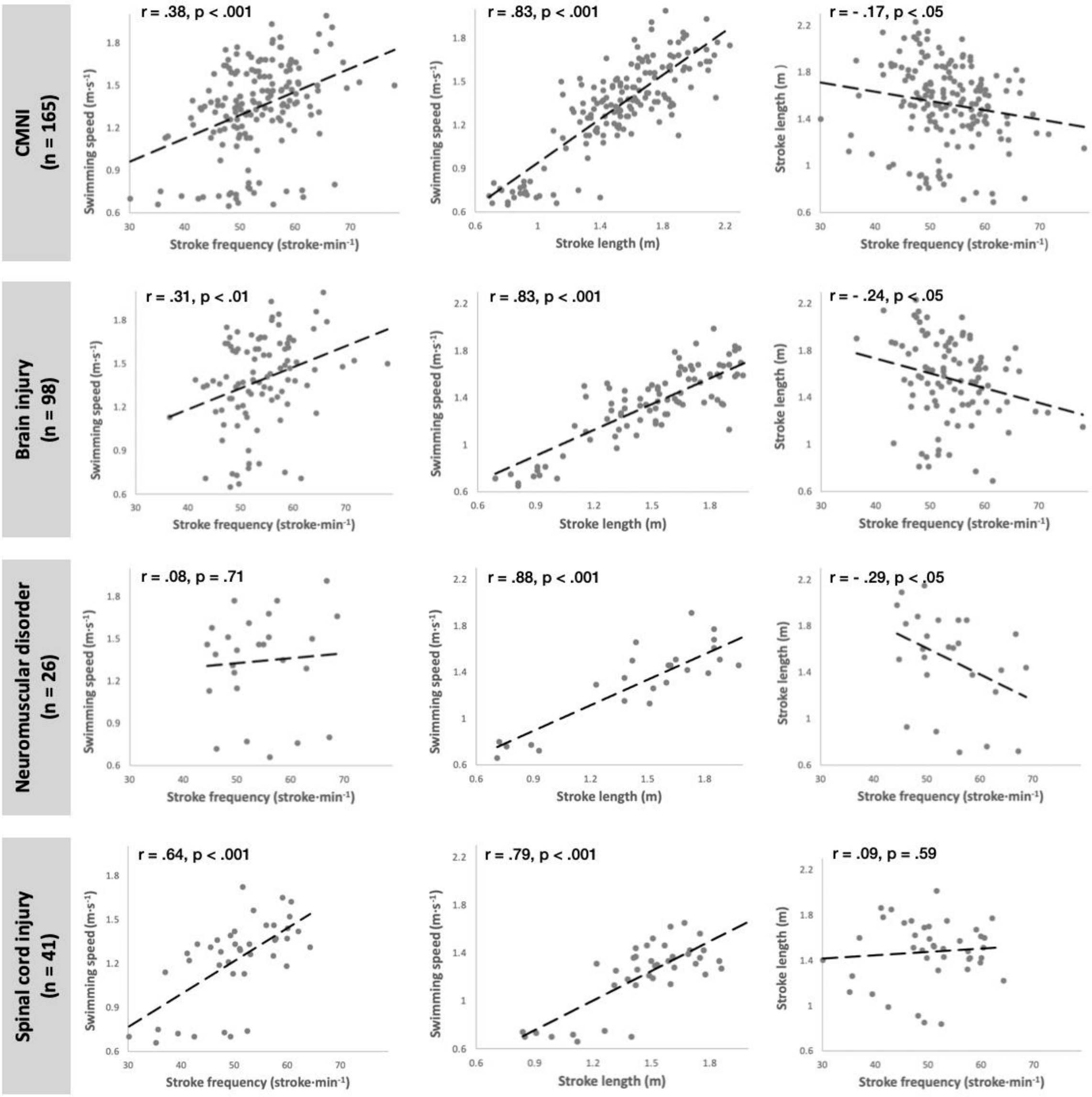


Figure 3.3: Scatterplots of swimming speed, stroke frequency and stroke length for a pooled CMNI group (n = 165) and then sub-grouped into brain injury (n = 98), neuromuscular disorder (n = 26) and spinal cord injury (n = 41) in sprint freestyle swims (50 m & 100 m).

3.3.2 Paced swims (200 m & 400 m)

Effect of impairment severity

Moderate to large positive associations were found between swimming speed and sport class and between stroke length and sport class in CMNI swimmers collectively and in all three impairment sub-groups (τ = .43 to .63, p < .05; Figure 3.4). No association existed between stroke frequency and sport class in the CMNI group, or in the neuromuscular disorder and spinal cord injury sub-groups ($p > .05$). In the brain injury sub-group however, a small negative association was found between sport class and stroke frequency ($\tau = -.37$, $p < .01$).

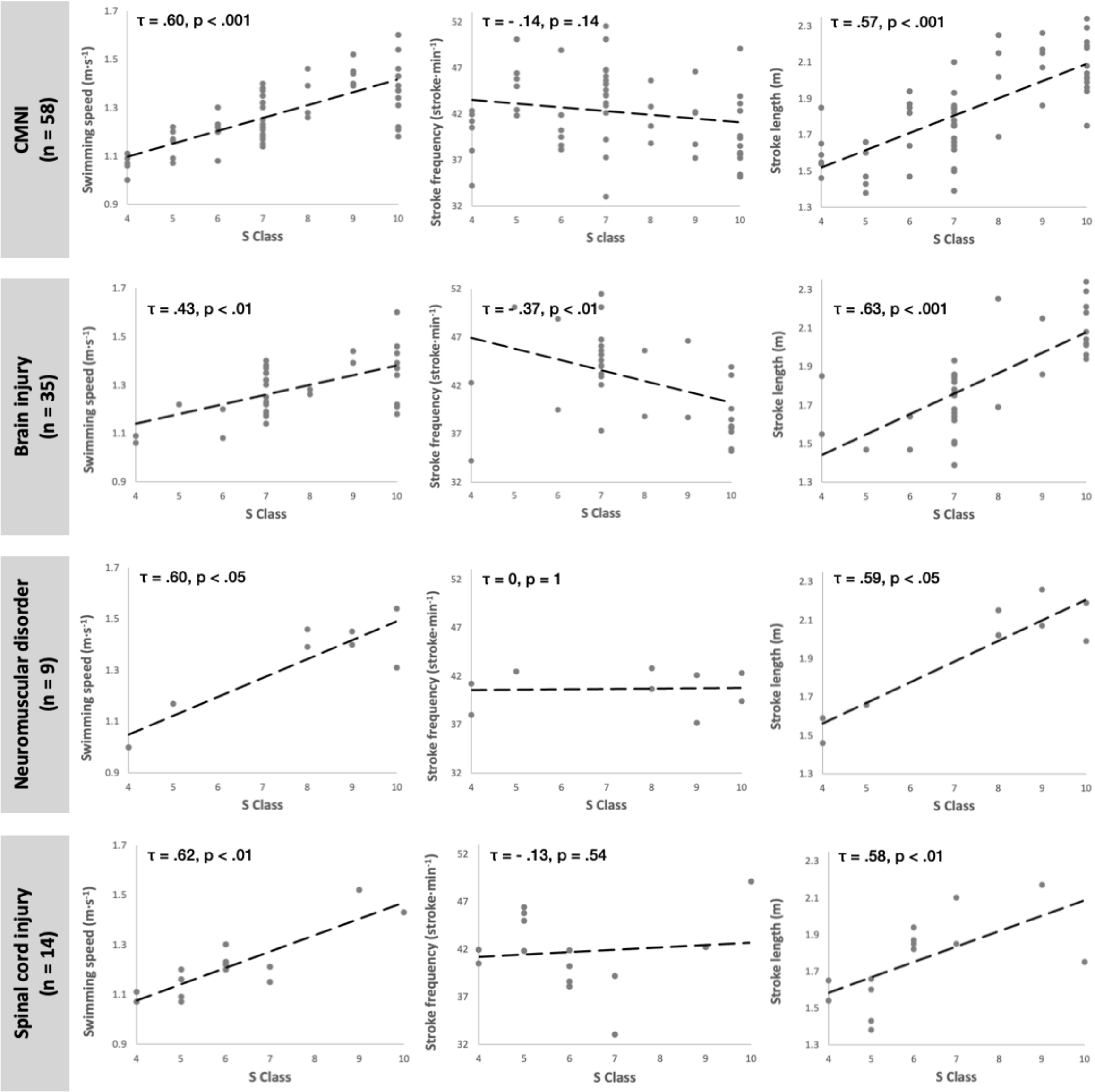


Figure 3.4: Scatterplots of swimming speed, stroke frequency and stroke length versus physical impairment sport class (S4–S10), presented as a pooled CMNI group (n = 58) and then sub-grouped into brain injury (n = 35), neuromuscular disorder (n = 9) and spinal cord injury (n = 14) in paced freestyle swims (200 m & 400 m).

Effect of freestyle variations and health condition

Differences in swimming speed ($X^2(2) = 13.961$, $p < .001$) and stroke length ($X^2(2) = 17.588$, $p < .001$) were found between the freestyle variations for the pooled CMNI group (Table 4.3). Both front crawl with bilateral kick and front crawl with unilateral kick had a greater swimming speed and stroke length than front crawl without kick ($p < .05$).

For health condition sub-groups, a significant difference in swimming speed was found within the front crawl with bilateral kick variation ($X^2(2) = 6.334$, $p = .042$). Post hoc tests showed that swimmers with neuromuscular disorder (using the bilateral kick variation) had significantly faster swimming speed than swimmers with brain injury (using the bilateral kick variation; $p < .05$). Within the front crawl without kick variation, stroke frequency ($X^2(2) = 9.498$, $p = .009$) differed between health conditions. Post hoc tests showed that swimming speed was greater in swimmers with brain injury (using the front crawl without kick variation) than those with neuromuscular disorder (using the without kick variation; $p < .05$), and that stroke frequency was greater in swimmers with brain injury (using the without kick variation) compared to swimmers with spinal cord injury (using the without kick variation; $p < .05$). No significant difference in stroke length was found between the health conditions for any freestyle variation ($p > .05$).

Table 3.3: Swimming speed, stroke frequency and stroke length (mean ± SD) for three freestyle variations, each sub-grouped into brain injury, neuromuscular disorder, and spinal cord injury in paced freestyle swims (200 m & 400 m; n = 58). Differences were shown as ^{a} from front crawl with bilateral kick; ^{b} from front crawl with unilateral kick; ^{c} from front crawl without kick; * from brain injury; $^{\#}$ from neuromuscular disorder; and § from spinal cord injury.

Freestyle variations	Swimming speed (m·s^{-1})	Stroke frequency (stroke·min^{-1})	Stroke length (m)
Front crawl with bilateral kick			
CMNI (n=13)	1.36 ± 0.11^{c}	41.0 ± 4.2	2.03 ± 0.19^{c}
Brain injury (n=7)	1.28 ± 0.10$^{\#}$	39.8 ± 4.4	1.99 ± 0.19
Neuromuscular disorder (n=5)	1.45 ± 0.06*	41.0 ± 2.3	2.14 ± 0.10
Spinal cord injury (n=1)	1.43	49.1	1.75
Front crawl with unilateral kick			
CMNI (n=17)	1.31 ± 0.12^{c}	41.6 ± 4.0	1.91 ± 0.26^{c}
Brain injury (n=15)	1.30 ± 0.11	41.8 ± 4.2	1.89 ± 0.27
Neuromuscular disorder (n=1)	1.31	39.4	1.99
Spinal cord injury (n=1)	1.52	42.2	2.17
Front crawl without kick			
CMNI (n=28)	1.21 ± 0.14^{ab}	43.0 ± 4.4	1.70 ± 0.20^{ab}
Brain injury (n=13)	1.28 ± 0.15	45.5 ± 4.4§	1.70 ± 0.20
Neuromuscular disorder (n=3)	1.06 ± 0.10	40.6 ± 2.3	1.57 ± 0.10
Spinal cord injury (n=12)	1.17 ± 0.07	41.0 ± 3.7*	1.72 ± 0.22

Associations between swimming speed, stroke frequency and stroke length

No associations existed between stroke frequency and swimming speed for any group ($p > .05$; Figure 3.5). Moderate to very large positive correlations were found between stroke length and swimming speed in CMNI swimmers collectively and in all health condition sub-groups ($r = .55$ to $.95$, $p < .05$). In addition, large negative correlations were found between stroke length and stroke frequency in CMNI swimmers collectively and in brain injury and spinal cord injury sub-groups ($r = - .62$ to $- .73$, $p < .05$).

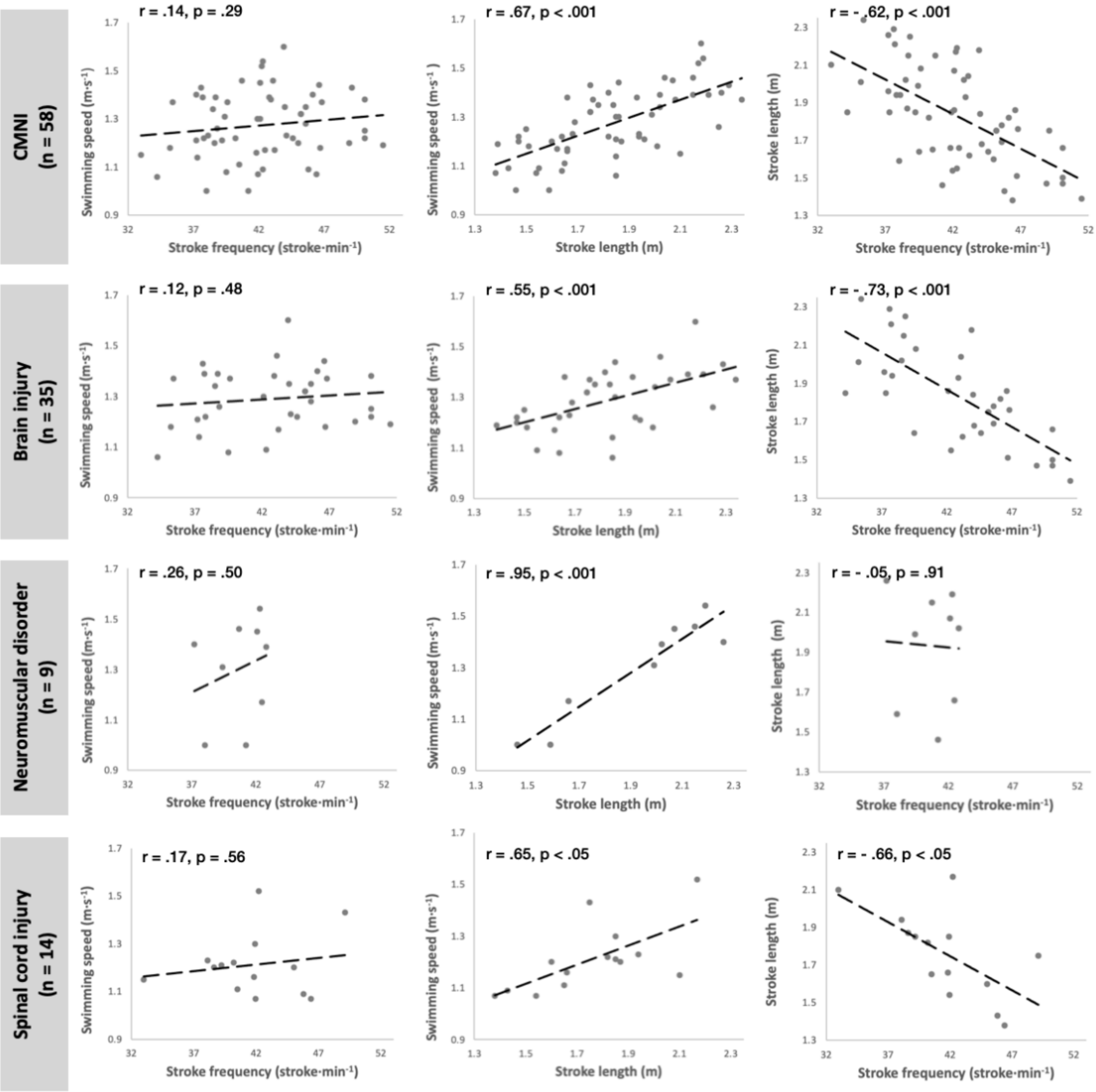


Figure 3.5: Scatterplots of swimming speed, stroke frequency and stroke length for a pooled CMNI group (n = 58) and then sub-grouped into brain injury (n = 35), neuromuscular disorder (n = 9) and spinal cord injury (n = 14) in paced freestyle swims (200 m & 400 m).

3.4 DISCUSSION

The current study investigated freestyle stroke parameters in highly trained swimmers with CMNI for the first time. The findings revealed that stroke length was positively associated with swimming speed in both sprint and paced swimming events, whereas stroke frequency was associated with swimming speed in sprint events only. Thus, swimming speed is influenced more by stroke length than by stroke frequency in CMNI swimmers, at least for paced swimming events. Moreover, associations exist between impairment severity (sport class) and swimming speed and stroke length in sprint and paced swims. Compared to less impaired swimmers, more impaired swimmers exhibited slower swimming speeds and shorter stroke lengths. The hypotheses were: (i) stroke length is the limiting factor to swimming speed in swimmers with CMNI and (ii) more impaired swimmers display shorter stroke length than less impaired swimmers do. As such, the two hypotheses were both accepted.

3.4.1 Non-disabled versus CMNI swimmers

Previous research has reported freestyle stroke parameters in non-disabled swimmers of national and international standard (Morais et al., 2022; Morais et al., 2019). These swimmers all used the front crawl technique, so for a valid comparison, only the CMNI swimmers who performed front crawl are included in the following discussion. The CMNI swimmers' swimming speed in both sprinting and paced events (1.42 and 1.27 $m \cdot s^{-1}$, respectively) were well below values reported for non-disabled male swimmers (2.00 and 1.63 $m \cdot s^{-1}$, respectively). While the sprinting stroke frequency in CMNI group was lower than that of non-disabled group (53.6 and 59.6 $stroke \cdot min^{-1}$, respectively), these two groups showed similar stroke frequency values in paced events (42.1 and 39.6 $stroke \cdot min^{-1}$, respectively). The stroke length differences between CMNI and non-disabled group, on the other hand, were substantially shorter both in sprinting events (1.43 and 2.02 m, respectively) and in paced events (1.84 and 2.50 m, respectively). Stroke frequency is swimming speed dependent (Silveira et al., 2017), therefore, it seems to be necessary for the CMNI swimmers to increase their stroke frequency in order to compensate their short stroke length. As the key to achieving faster swimming speed is to maintain long stroke length (Morais et al., 2022), the distance of race may elucidate the inability of CMNI swimmers to produce comparable stroke length to the non-disabled swimmers even with corresponding stroke frequencies. With stroke length being influenced by the propulsive and resistive (drag) forces acting on the swimmer (Craig and Pendergast, 1979), CMNI swimmers must be limited in their capacity to generate propulsion and/or minimise drag, compared to their non-disabled counterparts.

3.4.2 Effect of impairment severity (sport class)

To increase swimming speed in non-disabled swimmers, while stroke length is an essential factor for a long-term velocity improvement (Silva et al., 2013; Wakayoshi et al., 1993), stroke frequency is an important determinant of controlling the speed for the short term or maintaining the speed during a race (Figueiredo et al., 2013a). Accordingly, sprint speed is influenced by both stroke length and stroke frequency, whereas paced speed is influenced more by stroke length than by stroke frequency. This accords with the observations in the current study: swimming speed was associated with stroke frequency and stroke length in sprint swims, but the association between stroke length and swimming speed was stronger than that between stroke frequency and swimming speed. These results are consistent with those of a previous study which found stroke length had a greater influence on sprint swimming speed, than stroke frequency did, in swimmers with a range of physical impairments (Satkunskienė et al., 2005). For paced swimming, the current study showed swimming speed was associated only with stroke length, not with stroke frequency. Thus, swimming speed is influenced more by stroke length than by stroke frequency in CMNI swimmers.

As anticipated, as the severity of swimming-specific impairment decreased (sport class got higher) swimming speed and stroke length increased in CMNI swimmers, for both sprint and paced swims. These findings support previous results reported for groups of mixed physically impaired swimmers (Daly and Vanlandewijck, 1999; Feitosa et al., 2019; Pelayo et al., 1999; Santos et al., 2020a; Satkunskienė et al., 2005). Due to the nature of CMNI, most of the swimmers in this study do not have functional legs and so use techniques that are adapted according to their impairment severity and activity limitations. CMNI swimmer's stroke length, therefore, may be hindered by their reduced upper limb function and a weak or absent leg kick.

Surprisingly, a moderate positive association existed between stroke frequency and sport class in swimmers with spinal cord injury in sprint events, but not for swimmers with brain injury or neuromuscular disorder. This suggests that those with spinal cord injury may be disadvantaged in the CMNI population when sprinting. During paced events, a negative association between stroke frequency and sport class in brain injured swimmers showed that the more impaired brain injured swimmers were, the greater stroke frequency values these swimmers presented. In agreement with previous studies (Junior et al., 2018; Santos et al., 2020a; Satkunskienė et al., 2005), this may be a strategy for lower class swimmers with brain injury to obtain maximal swimming speed as they had shorter stroke length than higher class swimmers with brain injury did.

Some of the associations found between swimming speed, stroke length and stroke frequency were not consistent across the health condition and both sprint and paced events. It seems possible that these results are owing to different proportions among freestyle variations the swimmers used within each health condition. Since these swimmers may demonstrate a great range of stroke frequency and stroke length combinations as tactical movement patterns to compensate their deficiency, it might then be challenging to establish a trend.

3.4.3 Effect of freestyle variations

In freestyle, approximately 85% of total propulsion in non-disabled swimmers is produced by the upper limbs (Toussaint and Beek, 1992). Although the lower limbs are less effective than the upper limbs at generating propulsion in non-disabled freestyle, studies have highlighted that the kicking action can serve several useful roles: (i) contribute an amount of propulsion directly (Deschodt et al., 1999; Watkins and Gordon, 1983); (ii) generate a more powerful arm action (Watkins and Gordon, 1983); and (iii) maintain streamlined body position to minimise drag (Yanai, 2001b). Thus, the amount of leg functions a CMNI swimmer has will influence the stroke length they can achieve and, consequently, their swimming speed.

This influence of leg function on stroke length was evident in the current study. Reductions in stroke length and swimming speed were evident as the freestyle variations moved from bilateral or unilateral leg kick to no leg kick. Interestingly however, no difference in stroke length or swimming speed existed between front crawl with bilateral leg kick and front crawl with unilateral leg kick for both sprint and paced swims. Whilst swimmers with unilateral leg kick were missing contributions from one leg, they achieved a similar stroke length and swimming speed to those with bilateral leg kick. This suggests a comparable upper limb function between the two groups of swimmers, in order to achieve similar performance.

In paced events, swimmers with neuromuscular disorder swimming front crawl with bilateral kick swam faster than those in the brain injury group. It can be speculated that swimmers with neuromuscular disorder may have better tolerance towards fatigue compared to swimmers with brain injury as severe fatigue was the most common health issue in individuals with cerebral palsy (Benner et al., 2017). One interesting finding was that stroke frequency did not differ significantly between the five freestyle variations in either the sprint or paced swims. This indicates that stroke frequency is not restricted by CMNI swimmers’ activity limitations (different freestyle variations), supporting the notion that stroke length is more of a limiting factor than stroke frequency for these swimmers. Yet, this was not necessarily the case for the different impairment sub-groups within each freestyle variation. Swimmers with spinal cord injury had significantly slower stroke frequency compared to swimmers with brain injury within paced front crawl without kick variation. This result reinforces the suggestion that Para swimmers with spinal cord injury may be at a disadvantage within the CMNI population when they are competing with other impairment types in lower sport classes.

3.4.4 Limitations

Since CMNI swimmers are a small population in Para swimming, it is challenging to recruit viable sample sizes of male and female swimmers from all sport classes, freestyle events, impairment types and freestyle variations. Small sample sizes in some of the sub-groups meant that some statistical comparisons were not feasible, that male and female data were pooled and the analysis was sometimes limited to a qualitative assessment of the data. Another weakness of this study was the consistency of the performance level of the athletes. While the data from London Paralympic Games 2012 was the world-class performance level, the Great Britain Para swimming’s NEMO database was used to identify the best performance British swimmers achieved at any long course swimming event from European Championships to Paralympic Games during 2015–2022. These British swimmers were still at elite international level, however, not every swim we used for this study were from Paralympians.

3.5 CONCLUSION

Swimmers with CMNI were able to perform the stroke as fast as non-disabled swimmers did per minute, however, they exhibited significantly shorter stroke length and slower swimming speed. Stroke frequency was not influenced by impairment severity nor freestyle variation, but both stroke length and swimming speed were. As impairment severity increased (sport class decreased) stroke length and swimming speed decreased in both sprint and paced events. As such, stroke length is more of a limiting factor than stroke frequency is for CMNI swimmers. Future research should determine how CMNI swimmers generate propulsion and minimise drag, and if this differs from non-disabled swimmers in freestyle swimming. It is also important to establish the effect of CMNI severity and health condition on determinants of freestyle swimming, so that we may understand the constraints these swimmers may encounter in the water.

CHAPTER 4

GENERAL METHODS

This chapter describes the three-dimensional motion analysis used in studies 2–5 in detail, including participant information, participant preparation, experimental protocol, motion capture system and configuration, camera settings, calibration and data processing.

4.1 Participants

Data were collected on thirty highly-trained central motor and neuromuscular impaired (CMNI) Para swimmers from national swimming teams world-wide. To be included in the study, participants with CMNI had an eligible physical impairment resulting from cerebral palsy, spinal cord injury or other neuromuscular disorder, and hold a national or international swimming classification (S2–S9), be injury-free and be competing at a national or international level. The mean best long course time of CMNI swimmers was 43.2 ± 13.5 s for 50 m freestyle. Due to their impairment limitations, those who swam prone used a version of front crawl for their freestyle, and some swam supine. Nineteen swimmers performed front crawl using only their upper limbs, six used both upper limbs and one lower limb, two used all four limbs, and three performed a specialist freestyle technique – double-arm backstroke. The non-disabled group comprised thirteen swimmers ranging from national to Olympic level with a mean best long course time of 50.5 ± 2.5 s for 100 m freestyle. Details of all participants are presented in Table 3.1. The test protocol was explained fully to all participants, and they then provided written informed consent. The study was granted ethical approval by Manchester Metropolitan University, Faculty Research Ethics and Governance Committee (approval code 100517-ESS-HJ).

Table 4.1: Characteristics of non-disabled swimmers (n = 13) and swimmers with central motor and neuromuscular impairment (n = 30).

		Central motor and neuromuscular impairment	Non-disabled
Sex	*Males*	n = 19	n = 11
	Females	n = 11	n = 2
Age (yrs)		24.5 ± 5.6	22.0 ± 2.9
Height (cm)		165.5 ± 10.2	185.8 ± 6.7
Body mass (kg)		65.5 ± 12.2	82.8 ± 8.2
Sport class		S2 (n = 1) S3 (n = 2)[a] S4 (n = 6)[a] S5 (n = 4) S6 (n = 8) S7 (n = 2) S8 (n = 6) S9 (n = 1)	
Health condition		Cerebral Palsy (n = 15) Spinal cord injury (n = 10) Neuromuscular disorder (n = 5)	

[a] One S3 swimmer and two S4 swimmers performed double-arm backstroke.

4.2 Participant preparation

The participants were marked up by waterproof pen (body) and black tape (extremities) with 3 cm diameter circles of seventeen anatomical landmarks (head; right and left acromion (shoulder); medial and lateral epicondyles of the humerus (elbow); styloid processes of the radius and ulna (wrist); right and left middle finger tip; right and left greater trochanter (hip); right and left lateral femoral condyle (knee); right and left lateral malleolus (ankle); and right and left foot tip) (Figure 3.1). This marker set was used to define a fourteen-segment model of a swimmer, similar to the marker set applied by Puel et al. (2012) and Sanders (2002). Participants were instructed to wear a high cut swimsuit so the black markers could be applied directly to the skin to provide a clear contrast.

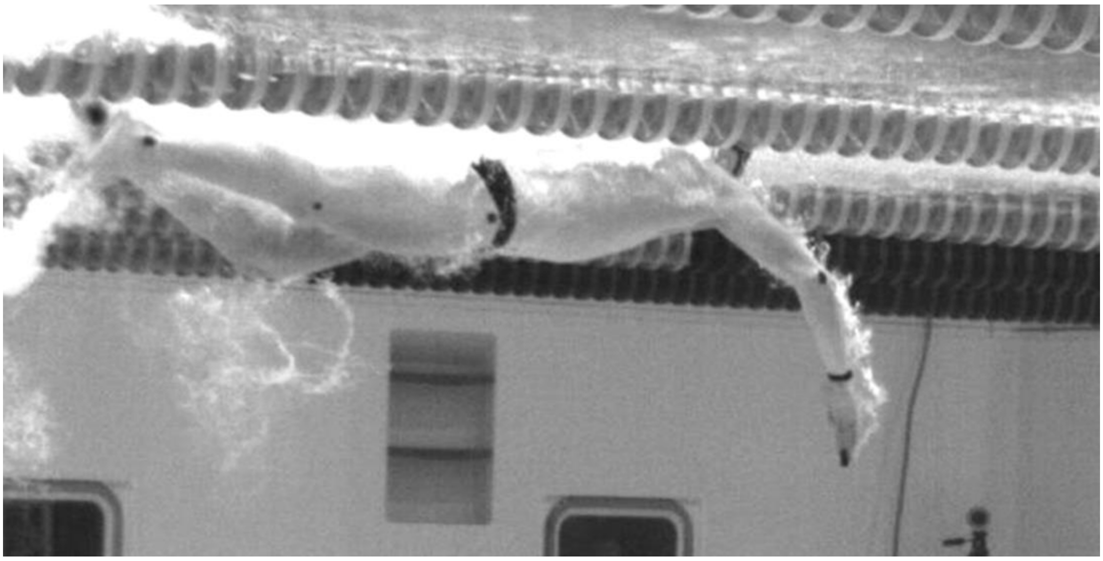


Figure 4.1: An example of anatomical landmarks.

4.3 Experimental protocol

Testing took place at six sites, in both 25 m and 50 m indoor pools with depths ranging from 1.8–2.0 m and temperatures typically around 28°C. Participants performed a warmup of self-selected volume and intensity that they would typically use before a race. Warm-up distance ranged from 100 m to 1000 m and was primarily influenced by the level of the swimmer’s impairment. Participants were tested in their training suits, with the majority also wearing a cap and goggles. Following warm-up, participants performed several 25 m front crawl trials at their 100–200 m race pace with at least 3 minutes’ rest provided between trials. Swimmers were asked to hold their breath as they swam through a calibrated performance volume.

4.4 Three-dimensional motion analysis

Motion capture system and configuration

Below water, trials were recorded via four full HD Ethernet cameras (Mako G-223B, Allied Vision Technologies GmbH, Germany) in waterproof housings (Nautilus IP68, Autovimation GmbH, Germany) mounted on tripods approximately 1 m below the surface. Cameras were connected to a PC through Ethernet cables and video data were captured to the hard drive and automatically synchronised using commercial software (Gecko GigE video recorder v1.9.4, Vision Experts Ltd, England). Above water, trials were recorded either by four additional full HD Ethernet cameras or full HD camcorders (Sony HDR-CX700, Sony Corporation, Japan). To synchronise above water cameras to those below, an LED system, fixed on the lane rope, was activated below and above the water in each trial. The LED system also served to synchronise individual camcorders when used for data collection. All cameras sampled at 50 Hz and exposure times were typically set at 1–4 ms depending on light conditions. Cameras were positioned on both sides of the pool in a similar configuration to that described in (O'Dowd et al., 2023) (Figure 4.2).

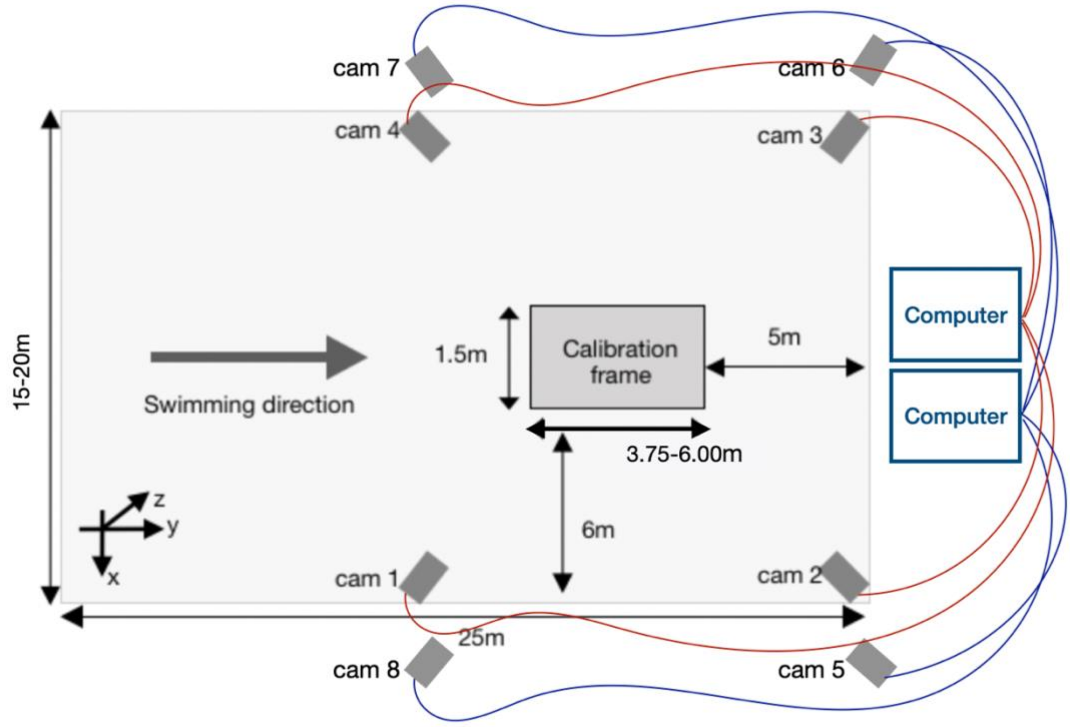


Figure 4.2: Schematic diagram of experimental set up.

Camera settings

Cameras were fitted with 12.5 mm C-Mount Megapixel Industrial Lens (Kowa LM12HC, Kowa Co Ltd, Japan). The focus and f-stop (iris) were set manually on the lens, whereas the shutter speed, gain and sample rate were controlled in the software. To provide non-blurred images of the fastest moving body segments in swimming, it is appropriate to have shutter speeds between 1/1000th to 1/250th of a second (Payton, 2008).

Cameras were set to a capture frequency of 50 Hz. This is considered an appropriate frame rate for a low frequency movement such as swimming (Payton and Burden, 2017) and has been used in many previous studies of swimming (Andersen et al., 2020; Figueiredo et al., 2012; McCabe et al., 2015). The sampling frequency must be at least two times the highest frequency present in the movement itself (Nyquist, 1928; Shannon, 1949). Moreover, Challis and Challis (2021) recommended that the capture frequency should be ten times greater than the highest frequency signal in the activity to avoid signal aliasing. A sufficiently high sample frequency is necessary to ensure the instances of maximum and minimum displacement of a joint or limb in a performance are recorded (Payton and Burden, 2017). Therefore, 50 Hz should be sufficient as front crawl stroke frequency was reported to be 0.74 Hz in non-disabled swimmers (Psycharakis and Sanders, 2008).

Calibration

A floating frame containing 108 control points was used to calibrate a performance volume (*x*: 1.50 m, *y*: 3.75–6:00 m, *z*: 1.80 m) and establish a global right-handed Cartesian coordinate system. The frame comprised 12 vertical rods each marked with 10 control points, 6 below water and 4 above (Figure 4.3). The *x*-axis was directed to the right side of the pool, the *y*-axis was in the direction of travel, and the *z*-axis was directed upward. The length (*y*-dimension) of the calibration frame was adjusted between testing sessions according to the width of the swimming pool and the camera field of view this permitted. This approach was adopted from a previous study by Payton et al. (2002). The calibration frame was recorded from all eight cameras at the start of each data collection session and then repositioned and recorded again at the end. All cameras were trained and focused on the calibrated volume. Challis (1995) suggested that extrapolations beyond small calibration volumes increase reconstruction errors, therefore, the large calibration volume in the study minimised the need for extrapolation, increasing the accuracy of the measurements (Psycharakis et al., 2010).

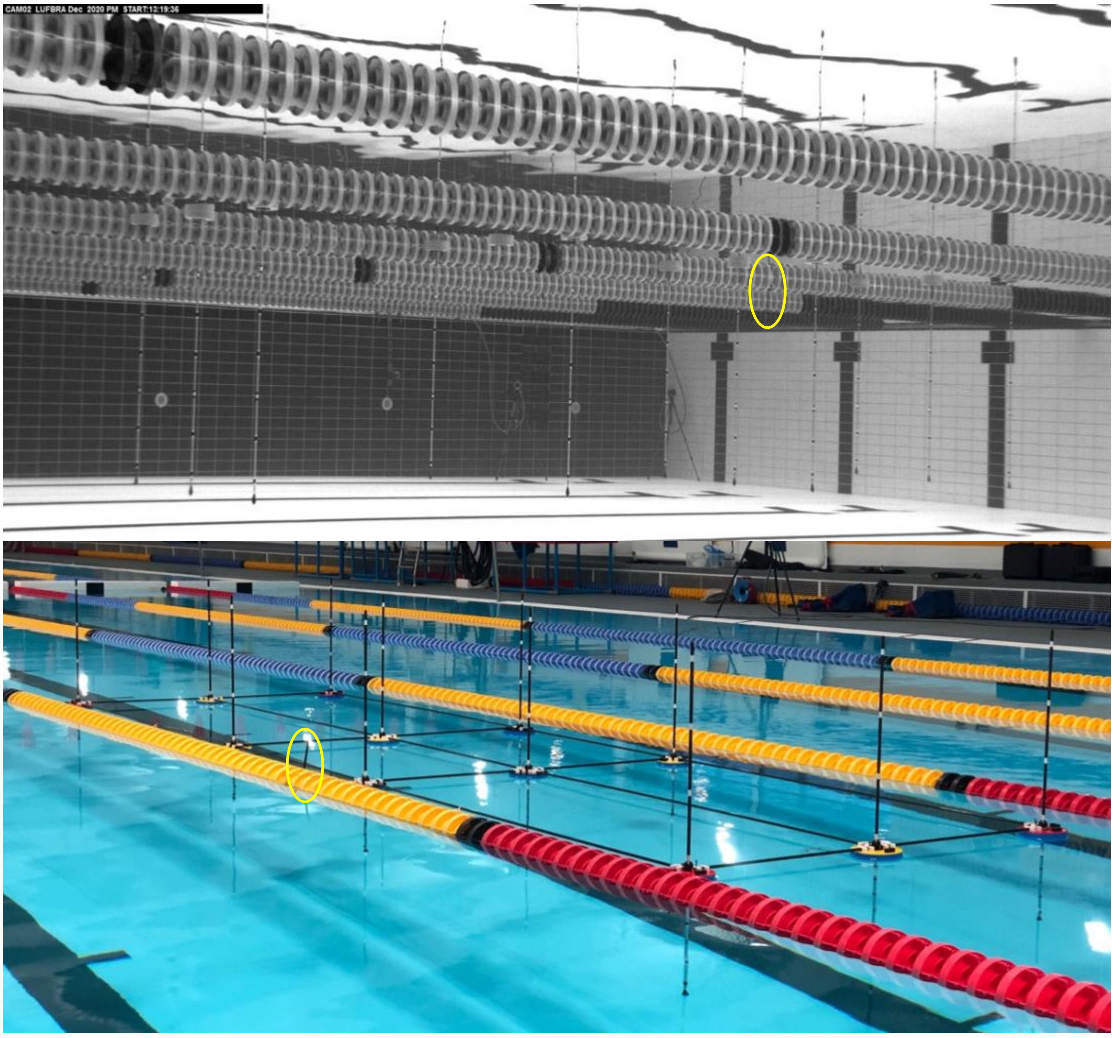


Figure 4.3: Below water and above water views of the calibration frame. The LED system use to synchronise above and below water cameras is circled.

4.5 Data processing

The seventeen anatomical landmarks, defining a 14-segment model of the swimmer, were digitised manually for each video frame (50 Hz) using SIMI Motion 3D (SIMI Reality Motion Systems GmbH, Unterschleißheim, Germany). Manual digitizing is practical in underwater environment where the contrast level of the marker is variable (Payton, 2008). Two-dimensional coordinates were transformed to real-world three-dimensional coordinates using the DLT method (Abdel-Aziz and Karara, 1971). A complete upper limb cycle was analysed, defined by consecutive entries of the same side hand into the water. The body segments' displacement, velocity and acceleration data for each point were determined by using SIMI 3D software, the location of the whole-body mass centre was estimated using the inertia data from De Leva (1996).

Displacement data were smoothed using a 2nd order Butterworth low pass filter with a cut-off of 7 Hz. Challis and Challis (2021) stated that it is necessary to remove the high frequency noise introduced by the digitizing process before any analysis can be taken. Butterworth digital filter have been widely used to smooth raw kinematic data in swimming (Gourgoulis et al., 2014; O'Dowd et al., 2023; Sanders et al., 2016) with a cut-off frequency ranging 4 Hz to 7 Hz. According to Sinclair et al. (2011) and Sinclair et al. (2013), determining a cut-off frequency should be based on 95% or 99% of signal power is contained below. Thus, 7 Hz as a cut-off can fall 95% of the signal power below and be appropriate to optimise precision.

To assess the accuracy of 3D coordinate reconstruction, 4 markers in the calibrated space were chosen randomly and were digitised over 10 frames for each underwater camera views. All reconstruction errors were obtained from the raw coordinate data without any smoothing procedure (Figueiredo et al., 2011; Scheirman et al., 1998). The Root Mean Square Error (RMSE) was then used to calculate the errors between the real and reconstructed coordinates. RMSE showed 7.3 mm for x-axis (0.5% of the volume); 4.0 mm for y-axis (0.1% of the volume); and 10.2 mm for z-axis (1.2% of the volume).

Psycharakis et al. (2005) reported RMSE of 3.8 to 4.8 mm of the calibrated space (representing 0.2%, 0.5% and 0.1% for the x, y, z direction respectively) and Coleman and Rankin (2005) reported RMSE of 5.1 to 9.8 mm (representing 0.5%, 0.3% and 0.4% for the x, y, z direction respectively) for a 6.60–6.75 m^3 volume. Our reconstruction errors for a calibrated volume of 8.44 m^3 were similar for x and y coordinates but higher for the z coordinate, compared to previously reported values. It is possible that the origin was digitised too low by 1–2 cm or the actual origin was 1–2 cm too low as the float on the frame was lower in that corner.

A complete stroke cycle was repeat digitised by the same operator, and then again by another experienced operator, to obtain intra- and inter-rater reliability in manual digitisation. Reconstructed 3D coordinates were used to calculate a range of kinematic variables relevant to this thesis (Table 4.2) and then the RMSE of the time series data obtained for each variable to quantify the magnitude of the discrepancy between the repeat measures.

Intra-tester RMSEs of 0.14–0.54 $m \cdot s^{-1}$ have been reported for wrist x and foot y velocity (Sanders et al., 2015) and 7–17 mm for wrist displacement in the x, y, z direction (Sanders et al., 2016). Intra-tester RMSEs of 0.95–3.45° were found for angular displacement of shoulder, hip, knee and ankle (Sanders et al., 2016). Our RMSEs for similar linear and angular kinematic variables were generally lower than these values and so the reliability of our measures were considered acceptable.

Table 4.2: Kinematic variables root mean square error (RMSE) for intra- and inter-tester reliability within one front crawl stroke cycle.

	Intra-tester reliability RMSE	Inter-tester reliability RMSE
Hand trajectory x (mm)	6	6
Hand trajectory y (mm)	5	7
Hand trajectory z (mm)	6	7
Hand speed x ($m \cdot s^{-1}$)	0.094	0.099
Hand speed y ($m \cdot s^{-1}$)	0.073	0.163
Hand speed z ($m \cdot s^{-1}$)	0.047	0.074
Elbow flexion (°)	2.61	2.50
Knee flexion (°)	1.70	1.78
Trunk inclination (°)	0.72	0.30
Thigh inclination (°)	0.82	1.26
Shank inclination (°)	1.07	0.85

The decision for pooling male and female swimmers in this thesis was made on the basis that: (i) there were insufficient numbers in the CMNI and non-disabled groups to conduct any meaningful analyses for the separate sexes; (ii) the majority of the key variables examined were not highly sex dependent, for instance, there is no evidence of sex effects on body roll amplitude (Vila Dieguez and Barden, 2020), Froude efficiency and intra-cyclic speed fluctuation (Zamparo et al., 2020), Index of Coordination, upper and lower limb joint angles, and orientation angles; (iii) the severity of cerebral palsy not appearing to be influenced by sex (Romeo et al., 2016); (iv) female/male participants were not proportionally distributed across ten sport classes; and (v) the nature of CMNI may involve high variability in swimmers' impairment type and severity (Hogarth et al., 2019a). Pooling of female/male swimmers could possibly provide more meaningful insights of their activity limitation in the water despite the known sex effects on swimming speed and stroke length (Knechtle et al., 2020). Where sex may be a confounding variable, this will be acknowledged in the relevant study's discussion.

CHAPTER 5

Study 2: The effect of central motor and neuromuscular impairment on front crawl kinematics in highly trained Para swimmers

5.1 INTRODUCTION

Para swimming has been featured since the first Paralympic Games in 1960 and is now one of the most popular and largest events in the Paralympic Games. Concerning a fair starting point for competition, a functional classification system is used to group swimmers with an eligible physical impairment into ten 'sport classes', with a lower number representing higher swimming-specific impairment severity (World Para Swimming, 2018). Classification is imperative in sports for athletes with a disability (Wu and Williams, 1999). The classification can be the dominant factor for the degree of success a Paralympic athlete could achieve (Tweedy and Vanlandewijck, 2011), hence lack of validity in the system can become a significant threat to the entire Paralympic movement. The International Paralympic Committee (IPC) thus mandated the development of a new evidence-based classification system in 2009 (Tweedy and Vanlandewijck, 2011).

To date there has been little agreement on the suitability of the current Para swimming functional classification system. First, classifiers determine the impact of impairment on swimming performance subjectively through land-based tests and a water assessment with a points-based system. Second, some Para swimmers' activity limitation may be underestimated as a result of the full battery of tests (strength, range of motion, and coordination) not often being used (Hogarth et al., 2019b). Third, the sport classes have been reported to be not equally competitive and fail to distinguish performance clearly between adjacent classes (Burkett et al., 2018; Daly and Vanlandewijck, 1999; Pelayo et al., 1999; Wu and Williams, 1999). Moreover, Oh et al. (2013) and Payton et al. (2020) identified a range of passive and active drag levels exist among Para swimmers within individual classes. These studies have evidenced that the current classification system disadvantages certain impairment types due to swimmers with various physical impairments (e.g., limb deficiency, impaired muscle power, hypertonia) competing together within a single class.

One population, swimmers with central motor and neuromuscular impairment (CMNI), is particularly difficult to classify objectively as how their impairment affects their movements in the water is understudied. Impaired range of motion (Connick et al., 2015), reduced muscle strength (Beckman et al., 2016) and poor motor coordination (Roldán et al., 2017) were all traits found in individuals with CMNI in land-based sports. However, the impact of CMNI type and severity on the determinants of swimming performance is relatively unknown (Tweedy et al., 2016). CMNI pathology can lead to distinctive, atypical motion characteristics including awkward, extraneous, uneven or inaccurate movements (Schmitz and O’sullivan, 2013). Hence, it can be speculated that swimmers with a CMNI, such as cerebral palsy, may find it difficult to perform the rhythmic and coordinated techniques required in swimming (Hogarth et al., 2019b).

Front crawl technique involves alternating cyclic movements of the lower limbs coordinated with the asynchronous movements of the upper limbs. In non-disabled swimmers, approximately 85% of total propulsion is produced by the upper limbs (Toussaint and Beek, 1992). Kinematic studies of non-disabled front crawl swimmers have generally focussed on variables linked to swimming performance, that is, those that reflect a swimmer’s ability to maximise propulsion and minimise drag during a stroke cycle. These include, for example, hand-path trajectory (McCabe et al., 2015; McCabe and Sanders, 2012; Payton et al., 1999; Vezos et al., 2007), elbow and shoulder motion (Haffner, 1998; McCabe et al., 2015; McCabe and Sanders, 2012), and trunk inclination (Gourgoulis et al., 2014). It is well documented that faster swimmers achieve a greater stroke length than less proficient swimmers (Craig and Pendergast, 1979; Morais et al., 2022) and maintain a horizontal and lateral streamlined body position (Osborough et al., 2009). Compared to non-disabled swimmers, it is likely that CMNI swimmers would exhibit different front crawl characteristics owing to the nature of their impairment. To date, there are very few studies that have published detailed kinematic data on the freestyle techniques of CMNI swimmers.

Previous research has established that more physically impaired swimmers have shorter stroke lengths (Daly and Vanlandewijck, 1999; Feitosa et al., 2019; Pelayo et al., 1999; Santos et al., 2017; Satkunskienė et al., 2005), higher levels of strength asymmetry (Dingley et al., 2014), higher intra-cyclic speed fluctuation and lower propelling efficiency (Feitosa et al., 2019; O'Dowd et al., 2023) than less impaired swimmers. Although valuable, these studies fail to address the relationship between front crawl performance and the broad range of type and severity of impairment separately. While Feitosa et al. (2019) attempted to specify the impact of physical disability on swimming performance, this study was restricted to case-by-case qualitative investigation considering its small sample size (n = 11, including four CMNI swimmers) and great variation in physical impairments. It was thus challenging to identify the impacts of CMNI quantitatively in the water. By contrast, Payton et al. (2020) investigated active drag in swimmers with CMNI as one specific population. These authors revealed that CMNI influenced active drag and the swimmer’s ability to interact with the water, highlighting that CMNI limits swimming speed by affecting both propulsion generation and drag reduction.

To achieve an evidence-based classification system, one essential step according to the IPC Position Stand, is to develop standardised and swimming-specific measures of determinants of performance (Tweedy et al., 2014; Tweedy et al., 2016). This study will help identify those biomechanical factors that limit front crawl performance in CMNI swimmers. The aims of this study are to: (i) establish whether differences exist in front crawl kinematics between non-disabled swimmers and those with CMNI, and (ii) assess the effect of central motor and neuromuscular impairment on front crawl kinematics. It is hypothesised that: (i) Front crawl kinematics differ between CMNI swimmers and non-disabled swimmers and, (ii) impairment severity and impairment location influence CMNI front crawl kinematics.

5.2 METHODS

5.2.1 Participants

Twenty-seven highly trained CMNI swimmers and thirteen non-disabled swimmers participated in this study. These twenty-seven CMNI swimmers were the subsample of swimmers that performed front crawl as their freestyle technique, the remaining three CMNI swimmers performed double-arm backstroke, which was examined in chapter 8. For full details of the participants please see chapter 4 – General Methods.

5.2.2 Data collection protocol

See chapter 4 – General Methods – for equipment details, pool calibration, video capture, video digitising and data processing methods.

5.2.3 Data analysis and definition of variables

One stroke cycle, a complete cycle of the upper limbs, defined by the period between one hand entry into the water and next hand entry of the same hand, was analysed. The upper limb cycle was divided into four phases for both sides (McCabe et al., 2015): (i) *glide*: from wrist entering the water to the first backward movement of the wrist (y-axis) relative to the global reference system (ii) *pull*: from end of glide to wrist vertically aligned (y-axis) with the glenohumeral joint, (iii) *push*: from end of pull to last backward movement of the wrist (y-axis) relative to the global reference system, and (iv) *recovery*: from end of push to wrist re-entry to the water. Each phase duration was expressed as a percentage of the upper limb cycle time. The following variables were calculated: (i) *mean swimming speed* (v_{MEAN}): mean speed of the whole-body mass centre in the y-direction, (ii) *stroke frequency* (*SF*): reciprocal of the upper limb cycle time multiplied by 60, (iii) *stroke length* (*SL*): displacement of centre of mass in the y-direction during an upper limb cycle.

Upper and lower limb kinematic variables were calculated for both right and left sides to identify any bilateral asymmetries in the swimmers' motions. These variables were chosen to be the predictors of propulsion generation or drag reduction for front crawl performance. Underwater hand trajectory dimensions were quantified by considering the displacement of the hand mass centre in all three dimensions: *hand trajectory width* (m) – medial displacement (*x*-axis) of hand from its most lateral to most medial location relative to the global reference system, *hand trajectory depth* (m) – maximal negative vertical displacement (*z*-axis) of the hand relative to the water surface level, *hand trajectory length* (m) – backward displacement (*y*-axis) of the hand relative to a local reference system fixed at the mass centre, and *hand trajectory slippage* (m) – backward displacement (y-axis) of the hand relative to global reference system.

To quantify the position of the swimmers' hands as they entered and exited the water, the displacement of the wrists, in the x and y directions, were expressed relative to the same side glenohumeral joint at entry, and same side hip at exit as follows: (i) right/left hand entry position = ($x_{\mathrm{Wrist}} - x_{\mathrm{Shoulder}}$, $y_{\mathrm{Wrist}} - y_{\mathrm{Shoulder}}$) and (ii) right/left hand exit position = ($x_{\mathrm{Wrist}} - x_{\mathrm{Hip}}$, $y_{\mathrm{Wrist}} - y_{\mathrm{Hip}}$), where *x* and *y* denote the coordinates of the joint centres relative to the global, pool-fixed reference system.

Mean *hand speed* ($\mathrm{m \cdot s^{-1}}$) and *hand acceleration* ($\mathrm{m \cdot s^{-2}}$) in the pull and push phases were calculated relative to the global reference system, in the x and y directions. Locations of the swimmer's wrist entry and wrist exit were expressed relative to the same side shoulder and hip, respectively.

Elbow flexion angle (°) was defined as the arccosine of the dot product of the shoulder-elbow and elbow-wrist unit vectors. Elbow flexion angle was recorded at the temporal boundaries of the upper limb cycle phases from which *elbow flexion range of motion* (°) was calculated in the pull and push phases. *Peak elbow extension angular velocity* ($rad \cdot s^{-1}$) was quantified as the maximum extension angular velocity in the push phase. Shoulder and trunk motions have been previously linked to the generation of upper limb propulsion (Lecrivain et al., 2010; McCabe et al., 2015). Thus, *shoulder horizontal flexion* (°) and *shoulder roll* (°) were quantified at the start of the push phase. Shoulder roll was obtained by projecting the vector from the left to right glenohumeral joint centres onto xz plane of the global reference frame. The shoulder roll angle was then defined as the angle between this projected vector and the x-axis. Shoulder horizontal flexion was computed by projecting the vector linking shoulder and elbow onto the xz plane. The shoulder horizontal flexion was then obtained as: 180° ± (shoulder flexion° – shoulder roll°) at the start of the push phase.

Kick depth (m) was quantified, for each kick in the upper limb cycle, by subtracting the minimum vertical displacement (z coordinate) of the big toe from the level of the water surface. *Knee flexion angle* (°) was defined as the arccosine of the dot product of the hip–knee and knee–ankle unit vectors. Most of the CMNI swimmers (n = 19) in the current study performed freestyle using their upper limbs only. Peak knee flexion angle and peak knee extension angle were identified to illustrate the level of activity of the lower limbs. To assess the differences between right and left side, symmetry index (%) was defined as: $\frac{VARIABLE_{RIGHT} - VARIABLE_{LEFT}}{0.5(|VARIABLE_{RIGHT}| + |VARIABLE_{LEFT}|)} \cdot 100$, where 0% indicates full symmetry and > 100% indicates full asymmetry (Queen et al., 2020; Robinson et al., 1987). A symmetry index can exceed 100% and it is not bounded. If $VARIABLE_{RIGHT} <$

$VARIABLE_{LEFT}$, the value would be negative. As such, in the current study the absolute values of the symmetry index were reported.

To assess horizontal body alignment for non-disabled swimmers and those with CMNI, four inclination angles were calculated relative to the horizontal (xy) plane. These were: (i) *trunk inclination angle* (°) – mid-shoulder to mid-hip vector (Gourgoulis et al., 2014; Zamparo et al., 2009), (ii) *thigh inclination angle* (°) – mid-hip to mid-knee vector, (iii) *shank inclination angle* (°) – mid-knee to mid-ankle vector, and (iv) body inclination angle (°) – mid-shoulder to mid-knee vector.

Each inclination angle was determined as a mean value over the underwater phase, to demonstrate how the hand interact with propulsion and drag and further influence the body segment angle, as: $arctan\frac{(\text{Shoulder/Hip/Knee – Hip/Knee/Ankle})_Z}{(\text{Shoulder/Hip/Knee – Hip/Knee/Ankle})_Y}$.

5.2.4 Statistical analysis

The mean and standard deviation of all the variables were described for non-disabled and CMNI swimmers. Mann-Whitney U tests were used to test for differences in kinematic variables between these two groups. Within the CMNI group, associations between sport class and each kinematic variable were established using Kendall’s tau coefficients, which were interpreted such that ≤ .40 = small, .41 to .60 = moderate, .61 to .79 = large and ≥ .80 = very large (Mukaka, 2012). To examine differences in body/thigh inclination angles amongst three leg kick conditions in CMNI swimmers, Mann-Whitney U tests were used between without kick and with unilateral kick subgroups. As bilateral kick subgroup only involved 2 swimmers, it was not feasible to statistically analyse the difference with other subgroups. Multiple comparisons were made using Bonferroni correction post hoc pairwise comparisons. To assess the effect of kinematic variables on swimming performance, Pearson correlation coefficient was used to calculate the strength of association between variables. All analyses were conducted using IBM SPSS Statistics 28 software and statistical significance was set at $p < .05$.

5.3 RESULTS

This Results section is divided into two main parts. Part A will compare data from the CMNI swimmers to those from non-disabled swimmers; Part B will consider the effect of CMNI on front crawl swimming by looking at differences within the CMNI group.

5.3.1 Part A. Non-disabled versus CMNI swimmers

Spatiotemporal variables

Mean and standard deviation of kinematic and temporal variables for non-disabled and CMNI swimmers performing front crawl are shown in Table 5.1. On average the non-disabled swimmers were 0.80 $m \cdot s^{-1}$ (77%) faster than CMNI swimmers ($p < .001$). Stroke frequency and stroke length were also significantly greater in non-disabled swimmers than CMNI swimmers ($p < .001$). Relative durations of the stroke phases did not differ between the two groups.

Hand trajectory (Figure 5.1 and Table 5.2)

Figure 5.1 illustrates the trajectories of the left and right hand during an upper limb cycle. It is apparent that non-disabled swimmers had wider, deeper, and longer hand trajectories than CMNI swimmers did. Table 5.2 provides the dimensions of the hand trajectories during the underwater phase. Trajectory depth and trajectory length were, on average, 10 cm and 20 cm, respectively, greater in non-disabled swimmers than in CMNI swimmers ($p < .01$), whereas trajectory width was 5–8 cm higher in the CMNI swimmers ($p < .01$). Trajectory slippage did not differ significantly between the groups.

Hand speed and acceleration (Table 5.2)

None of the hand speed variables differed between non-disabled and CMNI swimmers ($p > .05$). Backward (y-axis) hand speed had negative values higher in pull phase than in push phase, denoting swimmers' hand accelerated in the pull phase then slowed down in the push phase. Backward hand acceleration during pull and push phases were significantly lower in CMNI swimmers compared to non-disabled swimmers ($p < .05$).

Elbow flexion and shoulder horizontal flexion angle (Table 5.2)

Elbow flexion angle at the start of the pull and elbow ROM within the pull phase were both 10° greater in CMNI front crawl than in non-disabled front crawl ($p < .01$). The magnitude of elbow flexion at all other instants during the underwater phase, and elbow extension within the push phase, were not significantly different between non-disabled and CMNI swimmers. There was a trend for the non-disabled swimmers to extend their elbows faster than CMNI swimmers within the push phase; on average 18% faster ($p = .052$). At the start of the push phase, non-disabled swimmers' left shoulders were 10–20° more horizontally flexed than were those of the CMNI swimmers ($p < .05$).

Lower limbs (Tables 5.1 and 5.2)

CMNI swimmers with bilateral kicks (243.2–268.7 kick·min^{-1}; n = 2) had much lower kick frequencies than non-disabled swimmers (313.1 ± 29.3 kick·min^{-1}). Knee flexion range of motion was 2 to 2.5 times more in the non-disabled group compared to the CMNI group ($p < .001$). Non-disabled swimmers' peak knee extension angle was greater than in swimmers with CMNI ($p < .001$). There was no significant difference between non-disabled and CMNI swimmers in peak knee flexion angle and kick depth.

Table 5.1: Kinematic spatiotemporal variables for non-disabled (n = 13) and central motor and neuromuscular impaired swimmers (CMNI; n = 27) in front crawl swimming. ^{a} represents a significant difference between the two groups.

	Non-disabled swimmers (n = 13)	CMNI swimmers (n = 27)
Mean swimming speed (m·s^{-1})	1.83 ± 0.13	1.03 ± 0.30 ^{a}
Stroke frequency (stroke·min^{-1})	52.2 ± 4.9	41.8 ± 9.2 ^{a}
Stroke length (m)	2.12 ± 0.14	1.47 ± 0.32 ^{a}
Glide phase (%)	34 ± 4	32 ± 9
Pull phase (%)	14 ± 2	16 ± 5
Push phase (%)	22 ± 3	23 ± 9
Recovery phase (%)	30 ± 2	29 ± 9
Kick frequency (kick·min^{-1})	313.1 ± 29.3	243.2 – 268.7 (n=2)

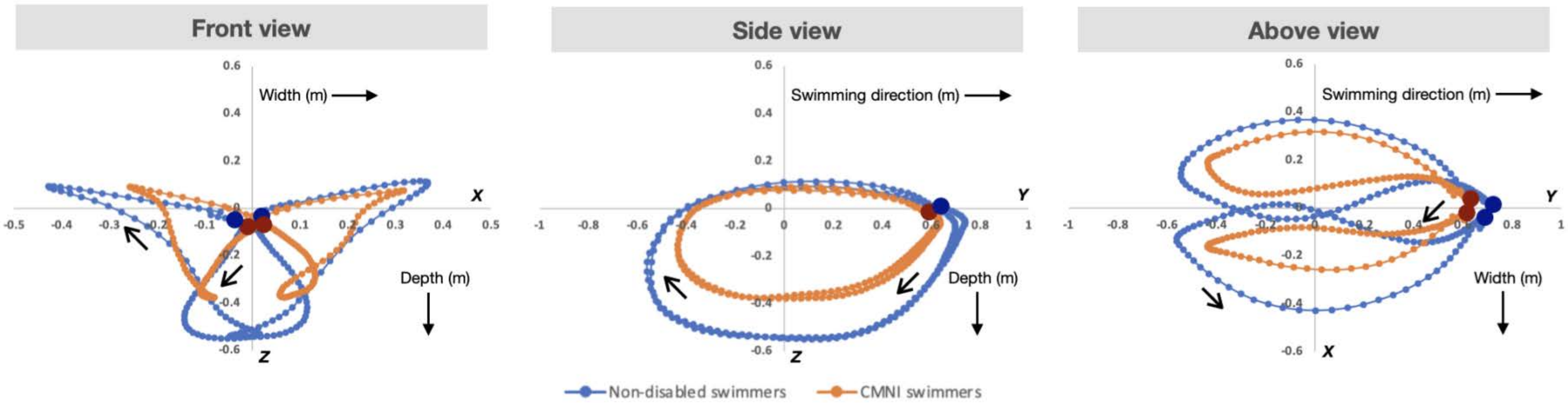


Figure 5.1: Left and right hand trajectories relative to a local coordinate system during a full upper limb cycle in front crawl. Views shown are front (y-axis), side (x-axis), and above (z-axis). Trajectories for the non-disabled group (n = 13) and central motor and neuromuscular impaired swimmers (n = 27) are mean curves. The dot denotes the hand entry and the arrow designates the direction of travel.

Table 5.2 Front crawl kinematic variables (mean ± SD) for left and right limbs and their symmetry index in non-disabled (n = 13) and central motor and neuromuscular impaired swimmers (CMNI; n = 27). [a] **and** [b] **represent a significant difference compared to non-disabled swimmers on the left and right side, respectively, and** [*] **represents a significant difference in symmetry index between non-disabled swimmers and swimmers with central motor and neuromuscular impairment.**

	Non-disabled swimmers (n = 13)			**CMNI swimmers (n = 27)**		
	Left	Right	Symmetry index (%)	Left	Right	Symmetry index (%)
Hand trajectory depth (m)	0.74 ± 0.06	0.72 ± 0.04	6 ± 6	0.64 ± 0.10 [a]	0.63 ± 0.09 [b]	9 ± 7
Hand trajectory width (m)	0.26 ± 0.06	0.26 ± 0.06	25 ± 15	0.34 ± 0.11 [a]	0.31 ± 0.10	27 ± 23
Hand trajectory length (m)	1.47 ± 0.06	1.48 ± 0.06	1 ± 1	1.28 ± 0.21 [a]	1.23 ± 0.25 [b]	10 ± 11 [*]
Hand trajectory slippage (m)	0.60 ± 0.10	0.65 ± 0.12	15 ± 14	0.66 ± 0.10	0.68 ± 0.16	14 ± 15
Mean hand speed x – pull (m·s^{-1})	0.92 ± 0.26	1.03 ± 0.40	28 ± 24	0.80 ± 0.27	0.82 ± 0.35	36 ± 24
Mean hand speed x – push (m·s^{-1})	0.80 ± 0.36	0.85 ± 0.27	38 ± 22	0.69 ± 0.24	0.70 ± 0.30	38 ± 29
Mean hand speed y – pull (m·s^{-1})	-1.32 ± 0.19	-1.46 ± 0.20	15 ± 11	-1.25 ± 0.31	-1.06 ± 1.24	24 ± 39
Mean hand speed y – push (m·s^{-1})	-1.10 ± 0.65	-1.31 ± 0.17	28 ± 52	-1.34 ± 0.35	-1.07 ± 1.17	29 ± 54
Mean hand acceleration y – pull (m·s^{-1})	-6.29 ± 1.62	-6.99 ± 2.40	43 ± 30	-4.89 ± 1.86 [a]	-5.29 ± 3.95 [b]	36 ± 36
Mean hand acceleration y – push (m·s^{-1})	10.46 ± 4.16	11.67 ± 4.77	19 ± 11	6.48 ± 3.78 [a]	7.58 ± 3.90 [b]	51 ± 58
Elbow flexion angle – start of pull (°)	141 ± 6	141 ± 11	6 ± 4	153 ± 8 [a]	151 ± 19 [b]	8 ± 14
Elbow flexion angle – start of push (°)	106 ± 5	104 ± 9	6 ± 5	106 ± 18	108 ± 20	10 ± 8
Elbow flexion angle – end of push (°)	139 ± 8	137 ± 11	6 ± 4	135 ± 14	128 ± 22	14 ± 19
Elbow flexion angle – hand exit (°)	144 ± 17	140 ± 16	7 ± 4	140 ± 17	129 ± 27	17 ± 26 [*]
Elbow flexion ROM during pull (°)	34 ± 6	37 ± 9	26 ± 19	47 ± 17 [a]	46 ± 20	26 ± 29
Elbow extension ROM during push (°)	32 ± 8	33 ± 10	113 ± 74	29 ± 20	31 ± 22	126 ± 73
Elbow peak angular velocity during push (rad·s^{-1})	5.25 ± 0.79	5.33 ± 1.02	12 ± 9	4.37 ± 1.74	4.61 ± 2.12	36 ± 36 [*]
Shoulder horizontal flexion – start of push (°)	151 ± 12	152 ± 13	8 ± 6	133 ± 26 [a]	142 ± 27	14 ± 10
Kick depth (m)	0.51 ± 0.05	0.50 ± 0.05	5 ± 5	0.47 ± 0.13	0.47 ± 0.11	13 ± 10 [*]
Peak knee extension angle (°)	191 ± 3	192 ± 4	1 ± 1	165 ± 25 [a]	168 ± 20 [b]	6 ± 7 [*]
Peak knee flexion angle (°)	142 ± 5	142 ± 7	4 ± 3	144 ± 27	148 ± 22	8 ± 8 [*]
Knee flexion range of motion (°)	49 ± 7	50 ±7	11 ± 8	20 ± 4 [a]	20 ± 10 [b]	55 ± 36 [*]

Symmetry index (Table 5.2)

The symmetry indexes for hand trajectory length, elbow flexion angle at hand exit position, elbow peak angular velocity during push, kick depth, knee flexion maximum and minimum angle, and knee flexion range of motion, were significantly greater in CMNI swimmers than in non-disabled swimmers ($p < .05$). CMNI swimmers were more asymmetrical in hand trajectory length, elbow angle at hand exit, elbow peak angular velocity during push and all lower limb variables than non-disabled swimmers.

Hand entry and exit (Figure 5.2)

As shown in Figure 5.2, non-disabled swimmers' hands entered the water approximately 10 cm more superior and 1 cm more lateral to the head, then exited the water 5 to 10 cm more inferior and 5 cm more lateral to the hip than CMNI swimmers' hand did. Hand entry of non-disabled swimmers was significantly more superior to the head than that of CMNI swimmers ($p < .05$).

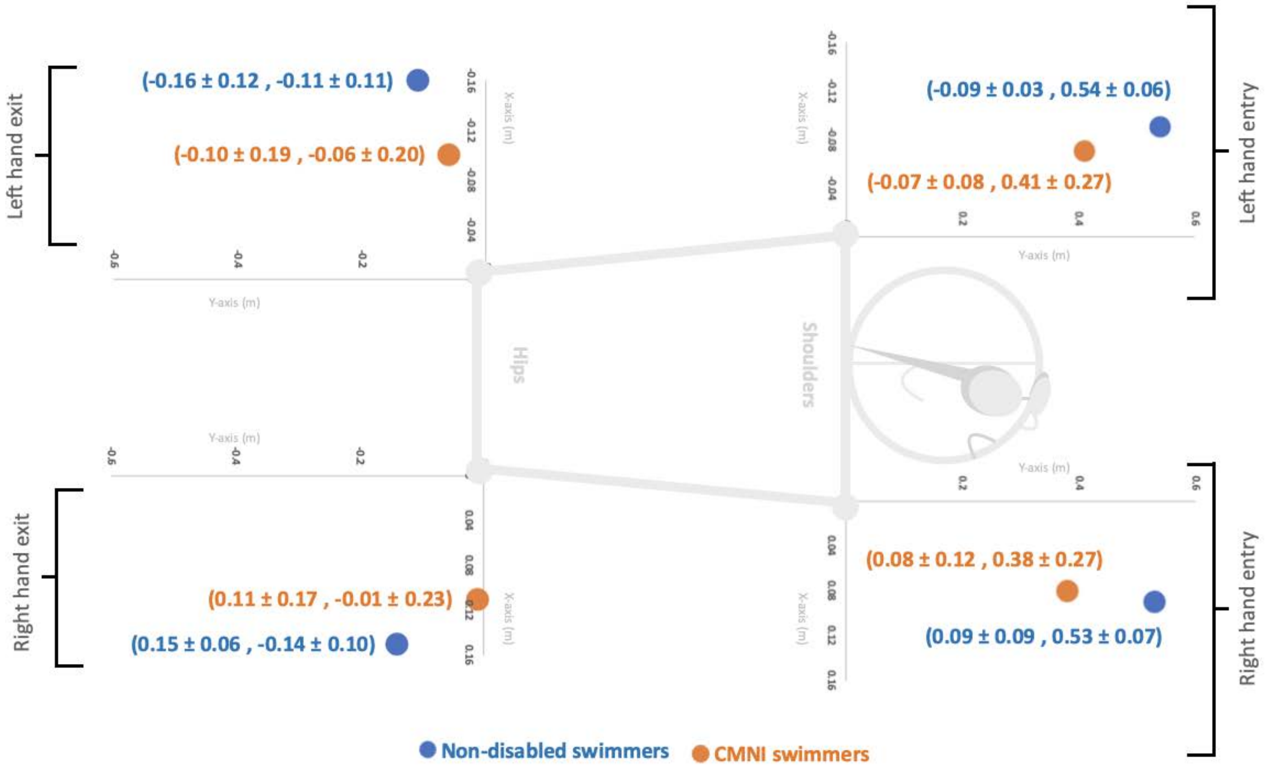


Figure 5.2: Location of hand entries (relative to same side shoulder) and hand exits (relative to same side hip) for non-disabled (n = 13) and central motor and neuromuscular impaired swimmers (n = 27) performing front crawl.

Body segment inclination angles (Figures 5.3 and 5.4)

While both groups had similar trunk inclination angles, Figure 5.3 illustrates that thigh (*p* < .01) and shank inclination (*p* < .05) of non-disabled swimmers was significantly different compared to that of CMNI swimmers, on average 10° lower and 4° greater, respectively.

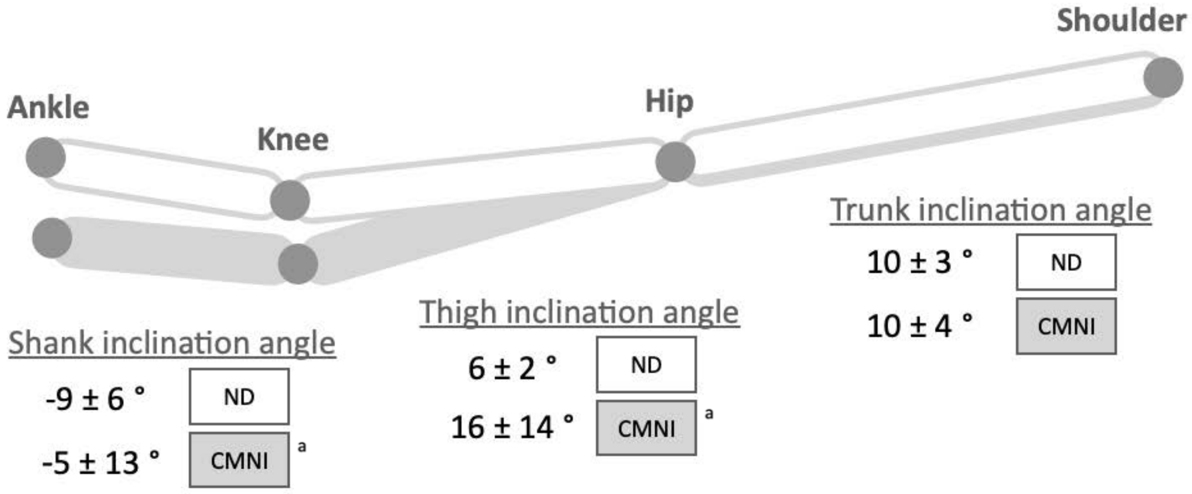


Figure 5.3: Mean body segment inclination angles during the underwater phase of front crawl for non-disabled (ND; n = 13) and central motor and neuromuscular impaired swimmers (CMNI; n = 27). [a] represents a significant difference compared to non-disabled swimmers.

The mean body inclination (shoulder to knee) for the whole underwater phase was greater in CMNI swimmers (16 ± 7°) compared to non-disabled swimmers (11 ± 2°) (*p* < .05; Figure 5.4). Non-disabled swimmers had their steepest body inclination at hand entry and at start of pull; conversely, CMNI swimmers had their steepest body inclination mid glide phase, on average, but they had 2 to 5 times higher variability in this variable compared to non-disabled swimmers.

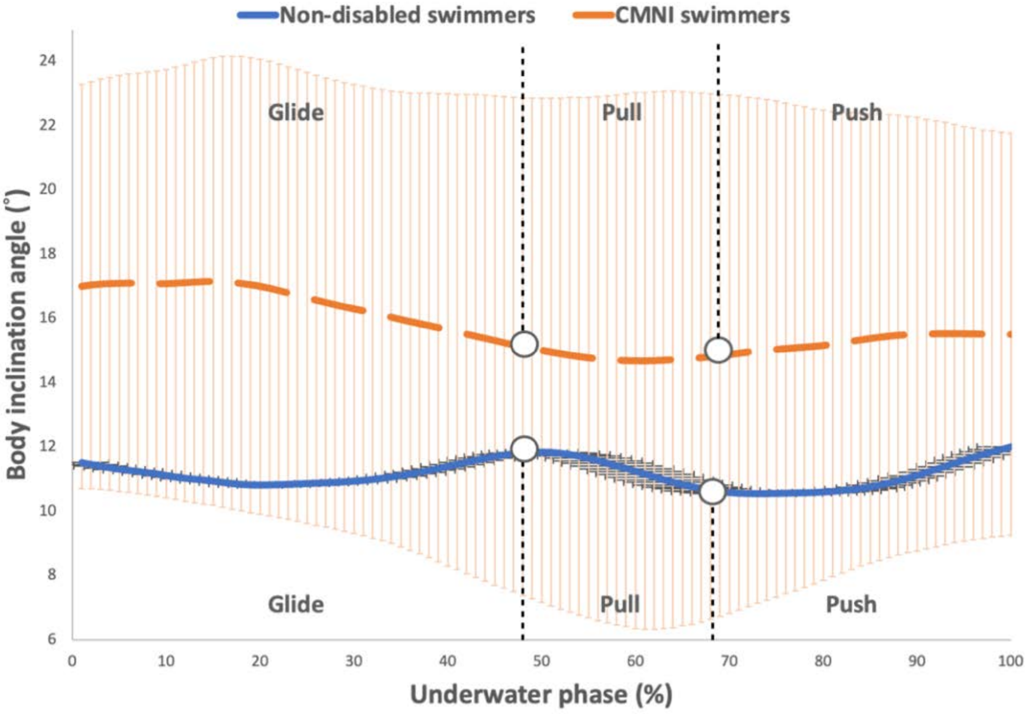


Figure 5.4: Mean and standard deviation of body inclination angle during the underwater phase of an upper limb cycle normalised to time for non-disabled (n = 13) and central motor and neuromuscular impaired front crawl swimmers (CMNI; n = 27).

5.3.2 Part B. Effect of CMNI on front crawl swimming

Swimming speed and stroke length had moderate positive association with sport class in CMNI swimmers ($\tau = .43$, $p = .003$ and $\tau = .40$, $p = .006$, respectively). However, stroke frequency did not differentiate between severities of CMNI (sport class; $p > .05$). More impaired swimmers (lower sport class) had shorter hand trajectory lengths ($\tau = .39 - .42$, $p = .004 - .009$) compared to less impaired swimmers (higher sport class). As Figure 5.5 shows, moderate negative associations were found between thigh inclination angle and sport class ($\tau = -.41$, $p = .005$) and between body inclination angle and sport class ($\tau = -.44$, $p = .002$). No association existed between sport class with trunk inclination angle and with shank inclination angle ($p > .05$).

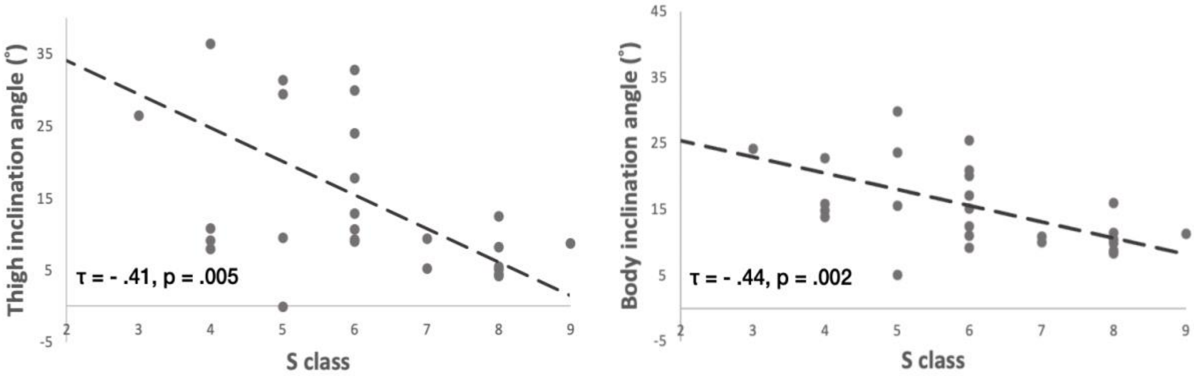


Figure 5.5: Scatterplots for thigh inclination angle (left) and body inclination angle (right) versus sport class for central motor and neuromuscular impaired swimmers in S2–S9.

Thigh and body inclination angles were significantly different between the three leg condition groups ($X^2(2) = 8.535$, $p = .014$ and $X^2(2) = 7.387$, $p = .025$, respectively; Table 5.3). Specifically, swimmers without a kick had 2 to 3 times greater thigh and body inclination angles compared to those with a unilateral kick ($p < .05$).

Table 5.3: Front crawl body inclination angles (mean ± SD) for swimmers with central motor and neuromuscular impairment (CMNI; n = 27), sub-grouped into three leg kick conditions: without kick (n = 19), with unilateral kick (n = 6), and with bilateral kick (n = 2). [a] represents a significant difference from group without kick; and [b] represents a significant difference from group with unilateral kick.

	CMNI swimmers (n = 27)		
	without kick (n=19)	with unilateral kick (n=6)	with bilateral kick (n=2)
Thigh inclination angle (°)	20 ± 14 [b]	6 ± 4 [a]	6 – 9
Body inclination angle (°)	18 ± 7 [b]	11 ± 4 [a]	9 – 11

Figure 5.6 provides six examples of CMNI swimmers who were diplegic and had difficulties maintaining a streamlined body position in the water during front crawl swimming.

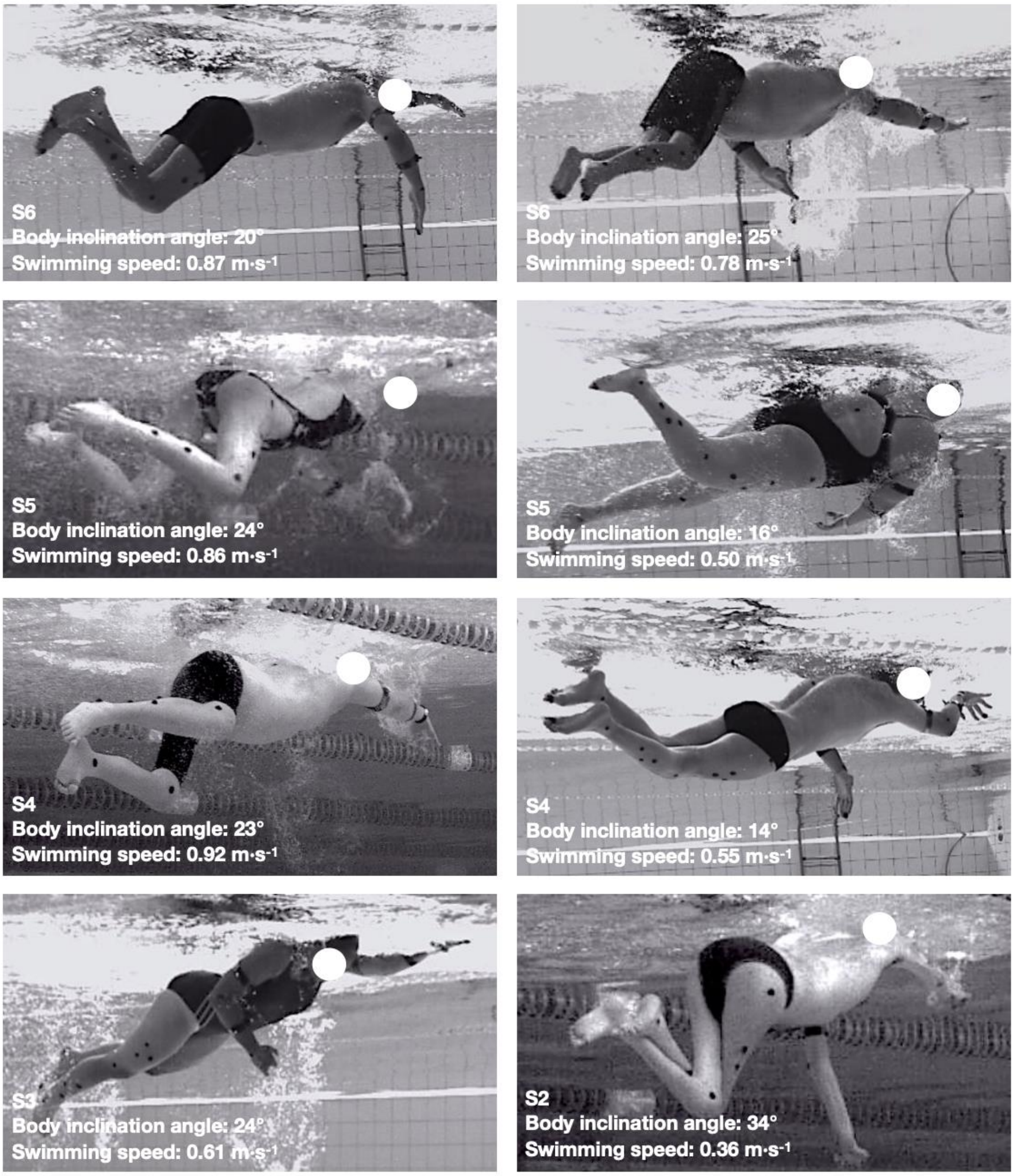


Figure 5.6: Examples of front crawl body positions for swimmers with central motor and neuromuscular impairment, presenting their sport class, body inclination angle and swimming speed.

Symmetry index

No association existed between impairment severity (sport class) and any of the CMNI symmetry indexes which differed from non-disabled swimmers previously ($p > .05$). Additionally, symmetry index did not correlate with swimming speed ($p > .05$).

Relationship between swimming speed, stroke frequency, stroke length, kinematic variables and body inclination angles

Swimming speed was positively correlated with stroke frequency (r = .71, p < .001), stroke length (r = .69, p < .001), hand trajectory depth (r = .41, p = .036), and hand trajectory length (r = .58, p = .002). Thigh and body inclination angles had moderate to strong negative correlations with swimming speed (r = - .56, p = .003 and r = - .62, p < .001, respectively) and stroke length (r = - .58, p = .002 and r = - .63, p < .001, respectively).

5.4 DISCUSSION

This study quantifies front crawl kinematic variables of CMNI swimmers and identifies the biomechanical factors that limit their swimming performance. The non-disabled swimmers had faster swimming speed, greater stroke frequency and longer stroke length compared to the CMNI swimmers. These differences can be explained by the differences in upper and lower limb kinematics between the two groups. Within the CMNI group, more impaired swimmers exhibited slower swimming speed and shorter stroke length. Particularly, the ability to maintain a streamlined body position decreased with an increase in impairment severity (sport class) and the absence of a kicking action. The two hypotheses: (i) CMNI swimmers have different front crawl kinematics to non-disabled swimmers and (ii) impairment severity and impairment location influences CMNI front crawl kinematics, were both accepted.

The stroke parameters found in this study did not fully support the findings from the previous study (chapter 3). Swimmers with CMNI had lower swimming speed and stroke length in both studies, however, the CMNI group exhibited lower stroke frequency than the non-disabled group in the current study while the stroke frequency did not differ between two groups in chapter 3. This inconsistency may be due to the differences in pace swimmers used during the data collection, performance level and impairment types. Both studies confirmed that CMNI impairment severity had an impact on swimming speed and stroke length. Stroke frequency, on the other hand, was not influenced by the impairment severity.

5.4.1 Upper limbs

Considering a greater hand acceleration induces greater propulsive forces (Gourgoulis et al., 2015), Kudo et al. (2023) explained the acceleration in faster swimmers was increased by the rapid changes in lateral and vertical hand motions and may further enhance propulsion, stroke length and stroke frequency. As such, our non-disabled swimmers exhibited higher swimming speed, stroke length and stroke frequency and likely had greater hand propulsion generation than CMNI swimmers. Interestingly, although hand speed is also a determinant of propulsive force generation in the water (Kudo et al., 2012), a greater hand speed does not guarantee a higher swimming speed as the swimmers may slip their hands though the water (Seifert et al., 2010c). Even though the hand speeds *relative to the water* did not differ between the two groups, CMNI swimmers must have generated slower backward hand speed *relative to the body* as non-disabled swimmers swam 77% faster than CMNI swimmers did. While non-disabled swimmers slipped ~40% the length of their hand trajectory, it was 10% more for CMNI swimmers. It seems that the ability to convert fast hand speed into high swimming speed and stroke length may be disturbed by CMNI.

Prior studies have identified factors that affect the hydrodynamics of a swimmer's hand include finger spacing (Marinho et al., 2010; Sidelnik and Young, 2006), thumb position (Bilinauskaite et al., 2013; Marinho et al., 2009), angle of attack (Marinho et al., 2011; Rouboa et al., 2006), and size of hand (Gourgoulis et al., 2008). These findings could help explain the reduced effectiveness of the upper limb motion in CMNI swimmers. While hand hydrodynamic forces were not investigated quantitatively in the current study, evidence of non-optimal hand shapes in the CMNI swimmers can be seen in Figure 5.6. To optimise hand propulsion, correct speed needs to be combined with a correct path (direction) and orientation (angle of attack and sweepback angle) of the swimmer's hand (Seifert et al., 2010c).

This study provides new insights into the upper limb cycle using coordinates to locate swimmer's hand entry to and exit from the water. CMNI swimmers had shorter hand entry and exit positions compared to the non-disabled swimmers. The above view of CMNI hand trajectory showed less wrist superior-inferior (y-axis) and mediolateral (x-axis) displacement above the water and the side view showed less glide following hand entry than those of non-disabled swimmers. CMNI seem to limit the upper limbs' capacity to stretch at the hand entry and extend fully at the hand exit. Consequently, their length and depth of hand trajectory were significantly lower than the values of non-disabled swimmers.

Contrary to expectations, the elbow flexion angle at all instants did not differ between non-disabled and CMNI swimmers, apart from at the start of the pull. Owing to the nature of CMNI, these swimmers' elbows may manifest stiffness (Levitt and Addison, 2018), impaired strength (Hogarth et al., 2019a), reduced extension (Bertelli and Ghizoni, 2015) and incomplete motor activation (McCartney, 1988). The more extended elbow of the CMNI swimmers at the start of the pull may be explained by them commencing elbow flexion later in the glide phase than the non-disabled swimmers. In addition, although the elbow flexion angles were comparable between the groups at the other instants in the cycle, CMNI swimmers did not present the same swimming speed and stroke length as non-disabled swimmers did. It is possible that the elbow stabiliser muscles of CMNI swimmers had lower strength to transmit the hydrodynamic forces from the hand to the body to enhance propulsion. Furthermore, there was a trend towards non-disabled swimmers extending their elbow faster than CMNI swimmers did during the push phase. The greater hand acceleration of the non-disabled swimmers in the push phase, compared to the CMNI swimmers, will in part be due to their higher elbow extension velocities in this phase.

Osborough (2012) asserted that the lower shoulder horizontal flexion observed during the push phase in unilateral arm amputee swimmers, compared to non-disabled swimmers, may be responsible for their reduced propulsion generation. Similarly, our CMNI group's shoulders were more horizontally flexed at the start of the push phase than those of the non-disabled group. This may be due to the differences in their body roll movements or the upper arm angle at that point. CMNI is often accompanied by impaired shoulder girdles (Tavernese et al., 2016), weakness of shoulder muscles (Burakgazi et al., 2019) and shoulder pain (Ferrero et al., 2015). It is thus likely that the CMNI group had restricted shoulder motion which would impact the amount of propulsion generated by upper limbs. Detailed analysis of the glenohumeral joint motion (flexion-extension, horizontal flexion-extension, internal-external rotation) is beyond the scope of this study, and further work needs to be undertaken to establish whether CMNI swimmers do in fact present abnormal shoulder motion.

5.4.2 Lower limbs

A ‘six beat kick’ (three cycles of each lower limb per upper limb cycle) is recommended for non-disabled front crawl swimmers as it facilitates a greater stroke length due to an increased body roll and a stabilised horizontal body position from which to achieve greater hand reach, superior to the head, at entry (Berger et al., 1999; Chollet et al., 1997; Costill et al., 1985; Gourgoulis et al., 2014; Sortwell, 2011). Although ~85% of propulsion in front crawl is generated by the upper limbs (Toussaint and Beek, 1992), an inconsistent or poorly coordinated kick may interrupt and diminish stroke length and stroke depth (Richards, 2006). Our findings support this opinion; the majority of impaired swimmers performed front crawl without an active kick and CMNI stroke length and depth of hand trajectory were lower than in non-disabled swimmers. More specifically, even though one swimmer with a bilateral kick had a similar stroke length to the non-disabled swimmers, his slower kick frequency still impeded his swimming speed which was 27% slower, highlighting lower limb dysfunction as one of the main limiting factors of performance in the CMNI group.

On average, the CMNI group achieved ~25° less peak knee extension compared to the non-disabled group, whereas both groups displayed a similar degree of peak knee flexion. This indicates that CMNI swimmers may have difficulties in extending their knees fully, whereas many of the non-disabled swimmers hyper-extended their knees during the cycle. Without an effective kick, CMNI swimmers are likely to experience imbalance of the trunk and this can result in inefficient arm movements as swimmers seek to gain stability in the water (Toussaint, 2002).

5.4.3 Body segment inclination angles

To the knowledge of the author of this thesis, this study is the first to investigate the trunk and body inclination of Para swimmers. These angles are important as poor horizontal body orientation will increase the frontal area presented to the water (Oh et al., 2013) and this will increase the drag experienced by swimmers (Kjendlie et al., 2004). CMNI swimmers exhibited poor body orientation in the water although using trunk inclination angle (shoulder–hip) to quantify their body position could be misleading for this population as some had their hips moderately close to the water level. Thus, body inclination (shoulder–knee) was chosen as a more appropriate metric to reflect CMNI swimmers' projected frontal area against the water, as this angle included the thigh inclination. Several factors can explain the poor body orientation observed in CMNI front crawl. For example, the absence of kick, the restricted knee and hip range of motion, and the affected trunk stability (Demir and Yıldırım, 2018; Levitt and Addison, 2018; Rath et al., 2018). In addition, the leg-sinking effect (torque), generated by the downward movement of the upper limbs (Schleihauf, 1983), may also increase the inclination of a swimmer's body. This is not an issue in non-disabled front crawl as the six-beat kick acts to counteract the leg-sinking torque generated by hand forces (Yanai and Wilson, 2008). However, most of our CMNI swimmers could not perform a kicking action, so they did not have the means of preventing their lower limbs/hips from sinking down.

It is worth noting that body orientation angles of both groups changed continuously within the underwater phase indicating that hydrodynamic forces were alternating between causing leg-sinking and leg-raising torques. The very high variability in body inclination angle within the CMNI group reflects the high variability in impairment type and severity of the group and impairment location. CMNI swimmers' body inclination was significantly greater than that of non-disabled swimmers. The non-disabled group were highly trained and included three Olympic Gold medallists. As such we can be confident that they were highly proficient in front crawl and that their body positioning was close to optimal. Their more horizontally aligned trunk and more extended lower limbs would result in them having lower drag coefficients (Kjendlie et al., 2004; Oh et al., 2013) and consequently a lower energy cost per unit distance (Zamparo et al., 2011) than the CMNI swimmers who presented with a less horizontally aligned trunk and more flexion in the lower limb.

Two technical modifications have previously been recommended by Yanai and Wilson (2008) to reduce the leg-sinking torque: (i) a smooth hand entry into the water (to reduce the vertical component of the hydrodynamic forces), and (ii) execution of the hand backward movement close to the body (to decrease the moment arm of the propulsive forces generated by the hands). Although CMNI swimmers appeared to pull their hands closer to their body than non-disabled swimmers did based on the depth of the pull and the angles of elbow and shoulder, they generally did not implement a smooth hand entry (evidenced in hand entry from Figure 5.2 and Figure 5.6). Along with the absence of kick, these differences could both contribute to the greater body inclination in the CMNI cohort.

The mean body inclination angle of the non-disabled swimmers stayed between 10 to 12°, which was less than the range of 6 to 16° reported by Gourgoulis et al. (2014). This disparity could be due to our definition of body inclination (shoulder–knee) differing from theirs (shoulder–hip) and also could be explained by participant differences between studies with respect to performance level, sex and anthropometric characteristics. Notably, both body inclinations became more horizontal during the pull phase. Since the swimmer's centre of mass and centre of buoyancy are not in alignment during swimming, a buoyant torque is generated by the interplay between the weight and buoyancy force on the swimmer's body. This torque serves to partially counterbalance the leg-sinking effect caused by hand forces during most of the stroke cycle (Yanai, 2001a). The leg-lifting buoyant torque seem to be greater than the leg-sinking effect caused by the hydrodynamic forces acting on the hand during pull phase, consequently, the body inclination decreased.

Within the CMNI group, thigh/body inclination angles were identified as key determinants of swimming speed and stroke length, with the strength of association being greater with body inclination than thigh inclination. This relationship between body inclination and swimming speed has also been reported for non-disabled swimmers by Stosic et al. (2021). As the severity of swimming-specific impairment increased (sport class got lower), so did the thigh/body inclinations. A previous study reported that larger active drag was negatively associated with slower and more impaired CMNI swimmers (Payton et al., 2020). As such, it can be speculated that CMNI swimmers with more inclined thigh/body positions would have greater active drag, limiting their swimming speed. It appears that thigh/body inclinations may be useful predictors of drag and thus performance, but further research is required to confirm the link among these variables.

CMNI swimmers who performed a kicking motion reduced their thigh and body inclination angles by 70% and 39% respectively, compared to swimmers without a kicking motion. Interestingly, the use of a unilateral kick achieved similar thigh/body inclination angles to those observed in swimmers with a bilateral kick. This indicates that the drag coefficients may be similar between these swimmers, however, the absence of a kick on one side could affect the propulsion from that leg and from the opposite side arm. Besides the effect of the kicking motion, Washino et al. (2021) reported that front crawl swimmers had larger trunk inclination when swimming with lower lung-volume level compared to swimming with maximum and intermediate lung-volume level. Considering that CMNI individuals with spinal cord injury have affected lung and respiratory function associated with their lesion level (Van Silfhout et al., 2016), it is possible that the spinal cord injured participants' high trunk/body inclinations may be partly attributable to limited lung-volume levels. The respiratory impairment in spinal cord injured patients with high cervical level injury are more severe and characterised by low lung volumes (Berlowitz et al., 2016). In the current study, two spinal cord injured swimmers with incomplete cervical level injury exhibited trunk inclination angles of 14–16° which were higher than the average angle in CMNI group.

Although greater body inclination is generally associated with slower swimming speeds and more impaired swimmers, there were some exceptions. Figure 5.6 illustrates that some swimmers in the same sport class presented with quite different lower limb segment orientations. This reflects different health conditions and impairment location with some participants, for example, presenting with muscle contractures and others with loss of trunk muscle control. Despite having a more inclined body position, some swimmers achieved faster swimming speeds than those who had more horizontally aligned bodies. It is likely that these swimmers compensate by generating relatively more propulsion to overcome the drag created by their body position. Body inclination is related to hydrodynamic forces, range of motion, as well as the ability to interact with the water in CMNI population. Future studies could examine these relationships in more depth.

5.4.4 Symmetry index

Compared to the non-disabled group, CMNI swimmers exhibited 2 to 10 times more bilateral asymmetry in their front crawl swimming, especially in their lower limb movements. Even though most of the CMNI swimmers (n = 19) had no active kick, the position of their lower limbs was not static in the water as their lower limbs oscillated within the upper limb cycle. However, it is unclear whether these lower limb motions were active or passive/deliberate or involuntary. As some of the motion patterns seem random, they did affect the symmetry index of CMNI swimmers. However, the more impaired, slower CMNI swimmers were no more asymmetrical than the less impaired, faster ones. Both non-disabled and CMNI swimmers displayed a certain degree of bilateral asymmetry, and it seems possible that asymmetry is a desirable characteristic of a swimmer’s technique that helps them optimise their own front crawl pattern. A previous study of backstroke has reported that the magnitude of asymmetry in the kinematics was not related to the swimmer’s performance. (Dias, 2022).

5.4.5 Limitations

This study is limited by the variable competitive performance levels of our CMNI swimmers. Although they were all classified, some only competed nationally or internationally in World Para Swimming European Championships whilst others were medallists at the Paralympic Games. As a potential confounding variable, the substantially larger proportion of males in non-disabled swimmers may contribute to the significant differences in swimming speed and stroke length compared to CMNI swimmers as those are the principle gender effects (Dormehl and Osborough, 2015; Seifert et al., 2007a; Toussaint et al., 2000). The study did not have access to the full medical records of the participants, which would have been beneficial in the analysis of their results. Furthermore, the estimation of the centre of mass is dependent on the precision of the anthropometric biomechanical model adopted. Care should be taken when choosing methods for centre of mass assessment and interpreting 3D data. Future studies of CMNI front crawl should: (i) examine the hand shape of CMNI swimmers and its effect on propulsion generation, (ii) determine the Froude efficiency and intra-cyclic speed fluctuation of CMNI swimmers to establish the propulsive effectiveness of their upper limbs, (iii) establish how CMNI swimmers roll their body to scrutinise their trunk function, and (iv) establish the relationship between body inclination and active drag.

5.5 CONCLUSION

This study set out to gain a better understanding of the biomechanical characteristics of highly trained swimmers with CMNI in front crawl swimming. CMNI swimmers exhibited significantly slower swimming speed, stroke frequency and shorter stroke length than non-disabled swimmers. Their front crawl performance was hindered by a shallower and shorter hand trajectory, affected propelling surface of the hand, lower hand backward acceleration, more restricted active range of motion at the shoulders and knees, dysfunctional lower limbs, and poor body orientations, compared to a non-disabled group. CMNI appears to affect both propulsion generation and drag reduction in front crawl. Within this impairment group, body and thigh inclination angles were found to differentiate between severity of swimming-specific impairment levels (sport class). Moreover, more impaired swimmers showed slower swimming speed, shorter stroke length and less horizontally aligned trunk and lower limb segments. Stroke frequency, however, was not associated with impairment severity.

CHAPTER 6

Study 3: Front crawl body roll characteristics of highly trained swimmers with central motor and neuromuscular impairment

6.1 INTRODUCTION

Front crawl techniques involve swimmers propelling themselves forward using alternating movements of the left and right upper limbs in the water. These movements incorporate a rotation of the trunk about its longitudinal axis, commonly referred to as body roll. This trunk rotation is essential for maximising front crawl swimming performance (Psycharakis and Sanders, 2010). Body roll involves rotation of the entire trunk combined with a twist of the trunk such that the hips and shoulders may achieve different amplitudes, possibly at different times in the stroke cycle (Yanai, 2001b). Body roll has been defined and quantified in a variety of ways (Gonjo et al., 2019; Lecrivain et al., 2010; Payton et al., 2002; Yanai, 2001b). A popular approach, when conducting kinematic analyses, is to quantify shoulder roll and hip roll by defining vectors through the two glenohumeral joints and hips joints, respectively (Gonjo et al., 2019; Yanai, 2001b). Alternatively, to help understand the kinetics of body roll, some researchers derive a total body roll angle through analysis of the whole body angular momentum (Lecrivain et al., 2010; Payton et al., 2002).

Body roll may facilitate the breathing action (Payton et al., 1999; Psycharakis and McCabe, 2011), aid recovery of the arm (Counsilman, 1968), increase propulsion (Kudo et al., 2017; Lecrivain et al., 2010), decrease hydrodynamic drag (Castro et al., 2003; Clarys, 1975) and reduce the risk of developing shoulder injuries (Vila Dieguez and Barden, 2020). As such, body roll has received considerable attention amongst researchers who seek to optimise front crawl skills.

Researchers have previously explored asymmetries in body roll and the association between body roll and swimming speed, stroke frequency, breathing action, skill level, and shoulder pain conditions, in non-disabled swimmers. The main findings from these studies are that: (i) national and international level male swimmers, at sprint to 400 m pace, exhibit a total hip roll range of 37 to 57° and a total shoulder roll range of 97 to 111°, when the roll amplitudes from both sides of the body are summed, (ii) the amplitudes of shoulder and hip roll both tend to decrease as swimming speed increases, (iii) body roll amplitude has a theoretical positive association with stroke frequency (Yanai, 2003) as stroke frequency is a controlling factor for attaining high speed within a race (Figueiredo et al., 2013a), (iv) swimmers roll their shoulders and hips significantly more to the breathing side than the non-breathing side, without changing the total amount of roll (Psycharakis and McCabe, 2011), (v) faster swimmers tend to roll their shoulders less than slower swimmers during a 200 m swim and roll asymmetry does not seem to affect swimming performance (Psycharakis and Sanders, 2008), (vi) swimmers with unilateral shoulder pain roll their hips significantly less compared to healthy swimmers (Vila Dieguez and Barden, 2020).

Given the influence of body roll on front crawl swimming performance it is important to understand the mechanisms responsible for generating trunk rolling movements. There are several potential causes of trunk rotation: (i) hydrodynamic forces (lift and drag) in medio-lateral and vertical (non-propulsive) directions create an external torque which changes the whole-body angular momentum about the longitudinal axis (Yanai, 2001b); (ii) internal muscle torques generate reaction torques in the opposite direction to those driving limb movements (Payton et al., 1999), which in fact restrain body roll and its amplitude, rather than create it (Yanai, 2001b); and (iii) the external torque produced by the buoyancy force. This occurs when the upper limb is above water during the recovery phase causing the whole-body centre of buoyancy to shift away from the whole-body centre of mass, forming a turning effect about the body's longitudinal axis. This mechanical cause is the primary source of body roll in non-disabled front crawl swimming and skilled swimmers are better able to utilise buoyancy force to generate body roll than less-skilled swimmers (Yanai, 2004).

Although body roll characteristics have been described quite extensively in non-disabled swimmers, knowledge of how swimmers with physical impairments roll their body in front crawl is limited (Gonjo et al., 2019; Lecrivain et al., 2010). In Para swimming, a functional classification system is used to assign swimmers with an eligible physical impairment to one of ten sport classes (World Para Swimming, 2018). As highlighted in chapter 1, the International Paralympic Committee mandated the development of new evidence-based classification systems in 2009 (Tweedy and Vanlandewijck, 2011).

Central motor and neuromuscular impaired (CMNI) swimmers are particularly challenging to classify objectively, as the impacts of impairment type and severity on the determinants of swimming performance have been under-researched. Individuals with CMNI are characterised by awkward, extraneous, uneven, or inaccurate movements (Schmitz and O'sullivan, 2013) so typically find it difficult to perform the rhythmic and coordinated techniques required in front crawl. It can be speculated that the body roll kinematics of CMNI swimmers may be profoundly different from those of non-disabled swimmers. Since CMNI is suggested to limit a swimmer's speed by affecting both their propulsion generation and drag reduction in the water (Payton et al., 2020), it is necessary to scrutinise their swimming movements to explain how CMNI affects front crawl swimming. To date, no study has investigated body roll kinematics in this population.

Given that a swimmer's movements in the water influence both the buoyancy and hydrodynamic forces (Yanai, 2004), and that these two forces directly influence body roll, it is hypothesised that CMNI swimmers display atypical body roll characteristics that differ from those of non-disabled swimmers. Quantifying CMNI body roll may demonstrate the degree to which impairment severity and impairment location disrupt front crawl performance. This study aims to: (i) compare body roll kinematics between non-disabled swimmers and those with CMNI, and (ii) examine the effect of impairment severity and impairment location on body roll.

6.2 METHOD

6.2.1 Participants

Twenty-seven highly trained CMNI swimmers (ten females and seventeen males) and thirteen non-disabled swimmers (two females and eleven males) participated in the current study. For further details on participants please refer to section 4.2.1.

6.2.2 Data collection protocol

After a warmup with self-selected volume and intensity, participants were instructed to perform 25 m front crawl trials at 100–200 m race pace from a push start. Participants typically completed two trials and were given at least 3 minutes rest between trials. Swimmers were asked to hold their breath as they swam through the calibrated performance volume as body roll has been shown to be affected by the breathing action (Payton et al., 1999) .

See chapter 4 – General Methods – for equipment details, pool calibration, video capture, video digitising and data processing methods.

6.2.3 Data analysis and definition of variables

Categorising upper limb and lower limb impairment severity

To explore any association between the impact of impairment severity and changes in shoulder roll and hip roll, the participants were first divided into three levels of arm impairment (AI) severity and then grouped again by their leg impairment (LI) severity derived from their swimming performance (Table 6.1). To quantify performance-derived AI severity, a Froude efficiency (η_F) was calculated for each CMNI swimmer to assess how effectively their upper limbs contribute to the propulsion (for details of calculation procedures for η_F, see section 7.2.3). The participants exhibited η_F ranging from 0.16 to 0.42 (see chapter 7) and were grouped using three thresholds (0.16–0.27, 0.27–0.35, 0.35–0.42): (i) AI_{severe}: lowest η_F performance group; (ii) $AI_{moderate}$: middle η_F performance group; and (iii) AI_{mild}: top η_F performance group. Performance-derived LI severity was determined by the number of legs the swimmer actively used during front crawl trials. CMNI swimmers were categorised into three groups: (i) $LI_{without\ kick}$: no-leg kick; (ii) $LI_{unilateral}$: one-leg kick; and (iii) $LI_{bilateral}$: two-leg kick.

Dependent variables

Mean swimming speed ($m \cdot s^{-1}$), stroke frequency ($strokes \cdot min^{-1}$) and stroke length (m) were calculated as described in section 5.2.3.

Shoulder roll angle (°) and *hip roll angle* (°) were obtained by projecting the vectors linking each bilateral joint pair (glenohumeral and hip) onto the xz plane perpendicular to the swimming direction (y-axis) and then calculating the angle between these projected vectors and the horizontal (Figure 6.1). The following body roll variables were then calculated for the shoulders and the hips: (i) *total roll* (°) – sum of the absolute values of the maximum and minimum roll angles within a stroke cycle; (ii) *roll asymmetry* (°) – the difference between the absolute values of the maximum and minimum roll angles within a stroke cycle; (iii) maximum *torso twist* (°) – the maximum difference between shoulder roll and hip roll within a stroke cycle; (iv) *range of torso twist* (°) – sum of the maximum magnitude of torso twist from the left and right sides within a stroke cycle; (v) *Roll Phase Lag* (% of stroke cycle) – time difference between occurrence of peak shoulder roll and hip roll amplitude to each side, expressed as a percentage of stroke cycle time. Roll Phase Lag defines how far the shoulder roll lags behind the hips, with positive values denoting hip rotation ending before shoulder rotation and negative values denoting shoulder rotation ending before hip rotation.

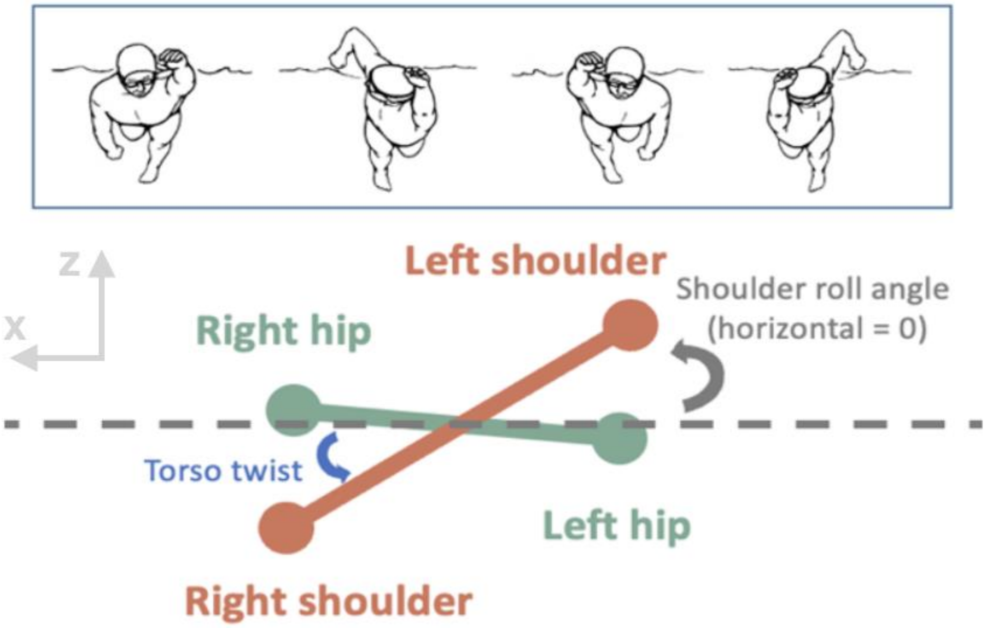


Figure 6.1: Definitions of shoulder roll, hip roll and torso twist.

6.2.4 Statistical analysis

IBM SPSS Statistics 28 was used to analyse the data. All data were checked for parametricity. Mann-Whitney U tests were performed to evaluate whether CMNI body roll metrics differ from those in non-disabled swimmers. Within the CMNI group, to compare the body roll metrics between three severity levels in arm impairment groups, one-way MANOVA was used. To compare the body metrics between three leg impairment groups, Kruskal-Wallis H test was used. As bilateral kick subgroup only involved 2 swimmers, it was not feasible to statistically analyse the difference with other subgroups. Multiple comparisons were made using Bonferroni corrected post hoc pairwise comparisons. Associations between S class and all the body roll kinematics were assessed using Kendall's tau coefficients, which were interpreted as ≤ .40 = small, .41 to .60 = moderate, .61 to .79 = large and ≥ .80 = very large (Mukaka, 2012). To assess the strength of association between swimming speed, stroke frequency, stroke length and body roll kinematics in CMNI swimmers, Pearson correlation coefficient was used. The threshold for statistical significance was set at *p*

$< .05$. Angle-angle plots were included to provide qualitative representations of body roll coordination over a full stroke cycle.

6.3 RESULTS

Table 6.1 presents discrete body roll variables for the non-disabled swimmer group, the overall CMNI swimmer group, and for the upper limb and lower limb impairment sub-groups. Mann-Whitney U tests revealed that mean swimming speed, stroke frequency, stroke length ($p < .001$), range of hip roll, range of torso twist, minimum torso twist ($p < .01$), range of shoulder roll, and maximum torso twist ($p < .05$) were significantly different between non-disabled and CMNI swimmers. Asymmetry in shoulder roll ($p = .067$) and in hip roll ($p = .076$) and roll phase lag did not differ between swimmers with and without an impairment.

Within the CMNI group, Froude efficiency was associated with swimming speed (F (2, 24) = 13.73; $p < .001$; partial $\eta^2 = .53$), stroke length (F (2, 24) = 10.52; $p < .001$; partial $\eta^2 = .47$), and stroke frequency (F (2, 24) = 5.26; $p = .013$; partial $\eta^2 = .31$). Swimming speed was significantly different between AI_{severe} and $AI_{moderate}$ groups ($p < .001$), and AI_{severe} and AI_{mild} groups ($p < .001$), but not between $AI_{moderate}$ and AI_{mild} groups ($p > .05$). The stroke length of the AI_{severe} group was significantly lower that AI_{mild} group ($p < .001$), however, no difference exists between AI_{severe} and $AI_{moderate}$ groups ($p > .05$), and $AI_{moderate}$ and AI_{mild} groups ($p > .05$). Stroke frequency, on the other hand, was different between AI_{severe} and $AI_{moderate}$ groups ($p = .011$), but not between AI_{severe} and AI_{mild} groups ($p > .05$), and $AI_{moderate}$ and AI_{mild} groups ($p > .05$). Range of hip roll, shoulder roll and hip roll asymmetry, torso twist, maximum and minimum torso twist, roll phase lag ($p > .05$) and range of shoulder roll ($p = .056$) did not differ between arm impairment sub-groups. No variables were significantly different between the three leg impairment sub-groups ($p > .05$). Moreover, no association was found between S class (swimming-specific impairment level) and any of the body roll metrics.

Table 6.1: Front crawl body roll kinematics (mean ± SD) for thirteen non-disabled swimmers and twenty-seven swimmers with central motor and neuromuscular impairment (CMNI), presented as a pooled group, three arm impairment sub-groups: AI$_{\text{severe}}$ ($\eta_F < 0.20$; $n = 9$); AI$_{\text{moderate}}$ (η_F 0.20 - 0.30; $n = 9$); AI$_{\text{mild}}$ ($\eta_F > 0.30$; $n = 9$), and three leg impairment sub-groups: LI$_{\text{without kick}}$ (no-leg kick; $n = 19$); LI$_{\text{unilateral}}$ (one-leg kick; $n = 6$); and LI$_{\text{bilateral}}$ (two-leg kick; $n = 2$). [a] denotes a significant difference between non-disabled and CMNI groups; [b] denotes a significant difference from AI$_{\text{severe}}$ group; [c] denotes a significant difference from AI$_{\text{moderate}}$ group; [d] denotes a significant difference from AI$_{\text{mild}}$ group.

	Non-disabled swimmers (n=13)	CMNI swimmers (n=27)	Arm impairment sub-groups (n=27)			Leg impairment sub-groups (n=27)		
			AI$_{\text{severe}}$ (n=9)	AI$_{\text{moderate}}$ (n=9)	AI$_{\text{mild}}$ (n=9)	LI$_{\text{without kick}}$ (n=19)	LI$_{\text{unilateral}}$ (n=6)	LI$_{\text{bilateral}}$ (n=2)
Swimming speed (m·s^{-1})	1.83 ± 0.13	1.03 ± 0.30 [a]	0.72 ± 0.23 [cd]	1.18 ± 0.24 [b]	1.18 ± 0.16 [b]	1.02 ± 0.31	0.96 ± 0.29	1.20 – 1.48
Stroke frequency (stroke·min^{-1})	52.2 ± 4.9	41.8 ± 9.2 [a]	36.1 ± 9.5 [c]	48.2 ± 8.7 [b]	41.1 ± 5.0	42.1 ± 10.6	40.7 ± 5.1	40.5 – 44.8
Stroke length (m)	2.12 ± 0.14	1.47 ± 0.32 [a]	1.21 ± 0.30 [d]	1.47 ± 0.20	1.73 ± 0.22 [b]	1.45 ± 0.28	1.42 ± 0.40	1.61 – 2.13
Range of shoulder roll (°)	102.3 ± 12.6	88.1 ± 21.3 [a]	101.7 ± 25.7	82.1 ± 15.9	80.4 ± 15.6	83.1 ± 18.2	105.0 ± 26.7	82.5 – 85.2
Shoulder roll asymmetry (°)	5.5 ± 4.3	9.7 ± 6.8	9.4 ± 6.3	9.5 ± 8.9	10.2 ± 5.7	10.2 ± 7.6	6.8 ± 3.8	12.8 – 14.2
Range of hip roll (°)	51.9 ± 6.6	74.9 ± 29.4 [a]	79.6 ± 27.1	60.0 ± 31.0	85.2 ± 26.6	71.1 ± 32.1	82.8 ± 17.4	61.7 – 114.0
Hip roll asymmetry (°)	4.9 ± 2.9	9.7 ± 7.9	11.3 ± 10.5	8.8 ± 7.0	9.0 ± 6.2	9.3 ± 9.1	10.5 ± 3.9	6.9 – 15.8
Range of torso twist (°)	61.4 ± 10.5	48.1 ± 22.1 [a]	49.5 ± 24.7	45.2 ± 19.6	44.2 ± 22.7	48.7 ± 21.6	49.7 ± 28.4	33.8 – 42.7
Left side max torso twist (°)	30.4 ± 7.8	24.3 ± 15.0 [a]	23.6 ± 16.8	24.1 ± 14.5	22.6 ± 15.3	24.7 ± 14.7	25.4 ± 19.3	15.4 – 19.6
Right side max torso twist (°)	31.0 ± 4.6	23.8 ± 9.4 [a]	25.9 ± 9.6	21.1 ± 8.2	21.6 ± 9.3	24.0 ± 9.9	24.3 ± 10.0	18.4 – 23.1
Roll Phase Lag (% of stroke cycle)								
SR$_{\text{MAX}}$ – HR$_{\text{MAX}}$ timing difference (greater shoulder roll side)	8.7 ± 9.1	4.0 ± 9.5	5.4 ± 9.4	0.7 ± 8.7	5.9 ± 10.6	3.4 ± 10.6	8.0 ± 5.5	-3.9 – 0
SR$_{\text{MIN}}$ – HR$_{\text{MIN}}$ timing difference (lesser shoulder roll side)	6.8 ± 10.6	1.0 ± 11.2	5.8 ± 11.0	-5.2 ± 11.9	2.4 ± 8.4	-0.5 ± 11.6	7.2 ± 9.9	-5.2 – -1.5

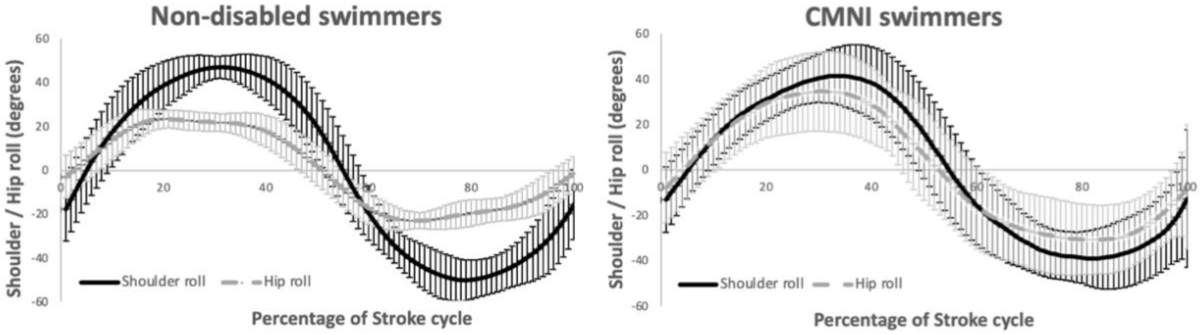


Figure 6.2: Shoulder and hip roll angles of non-disabled swimmers (*n* = 13; left) and CMNI swimmers (*n* = 27; right), normalised for one front crawl stroke cycle (mean ± SD). Curves begin (0%) at hand entry and end (100%) at the next same hand entry.

The general patterns of shoulder roll and hip roll for the non-disabled and CMNI swimmers are shown as ensemble averages in Figure 6.2. For both groups, following hand entry to the water the shoulders and hips rolled, in phase, to one side first then to the other, with the hip roll amplitudes being smaller than the shoulder roll amplitudes. The hips generally reached the neutral position (0° roll) slightly earlier than the shoulders, at around 50–55% of the stroke cycle. Non-disabled swimmers demonstrated less variable shoulder roll and hip roll curves.

6.3.1 Angle-angle plots of shoulder roll and hip roll

Angle-angle plots help highlight different coordination patterns in front crawl swimming. Specifically they can reveal whether: (i) the two quarters of stroke cycle to each side are symmetrical; (ii) shoulders and hips both achieve neutral (0°) positions at the same time; (iii) there is more than one peak in shoulder roll or hip roll amplitude or the peak maintains the same degree for a while; (iv) shoulders and hips both rotate in phase or out of phase; (v) amplitude differences exist between shoulder roll and hip roll. Additionally, the distance between successive points on the plots (equivalent to 0.02 s) provides a visual representation of the hip and shoulder roll angular velocities.

Figure 6.3 illustrates a typical hip roll versus shoulder roll angle-angle plot for a non-disabled swimmer along with the corresponding shoulder roll and hip roll normalised time histories. As no identical patterns of shoulder roll and hip roll existed in the CMNI group, five examples of angle-angle plots are shown in Figure 6.4. Comparing Figure 6.3 with 6.4, it is apparent that the non-disabled swimmer exhibited more symmetrical body roll with only one peak on each side, compared to CMNI swimmers. Example 1's hip roll peak lagged ~25% of the stroke cycle duration behind his shoulder roll peak; example 2 exhibited virtually no hip roll; example 3 had two peaks in his hip roll on each side; example 4 had relative noisy shoulder and hip roll curves; and example 5 had a hip roll magnitude as high as his shoulder roll.

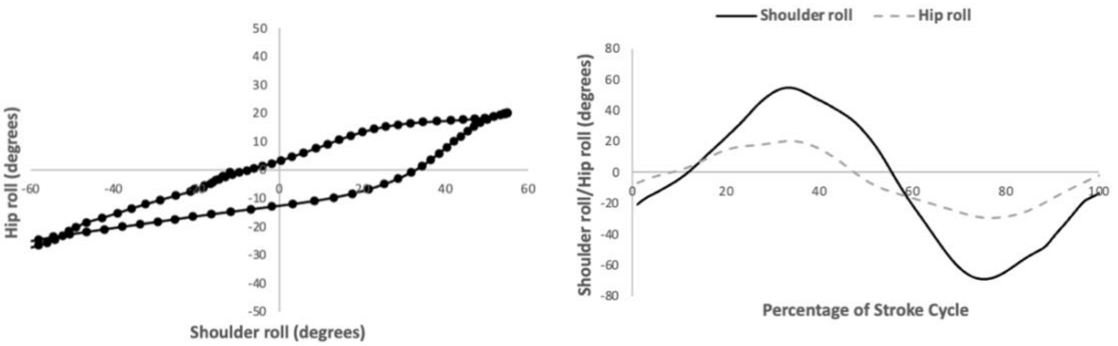


Figure 6.3: Example of a typical non-disabled swimmer's angle-angle plot of shoulder roll and hip roll for one front crawl stroke cycle (left) and its corresponding shoulder roll and hip roll pattern over a full stroke cycle (right).

6.3.2 Relationship between swimming speed, stroke frequency, stroke length and body roll kinematics in CMNI swimmers

Range of hip roll had a significant negative correlation with stroke frequency ($r = -.53$, $p < .01$) and a strong positive correlation with stroke length ($r = .41$, $p < .05$). However, stroke frequency and stroke length were not associated with range of shoulder roll ($p > .05$). Range of shoulder roll had strong positive correlations with range of hip roll and torso twist ($r = .39$ to $.42$, $p < .05$).

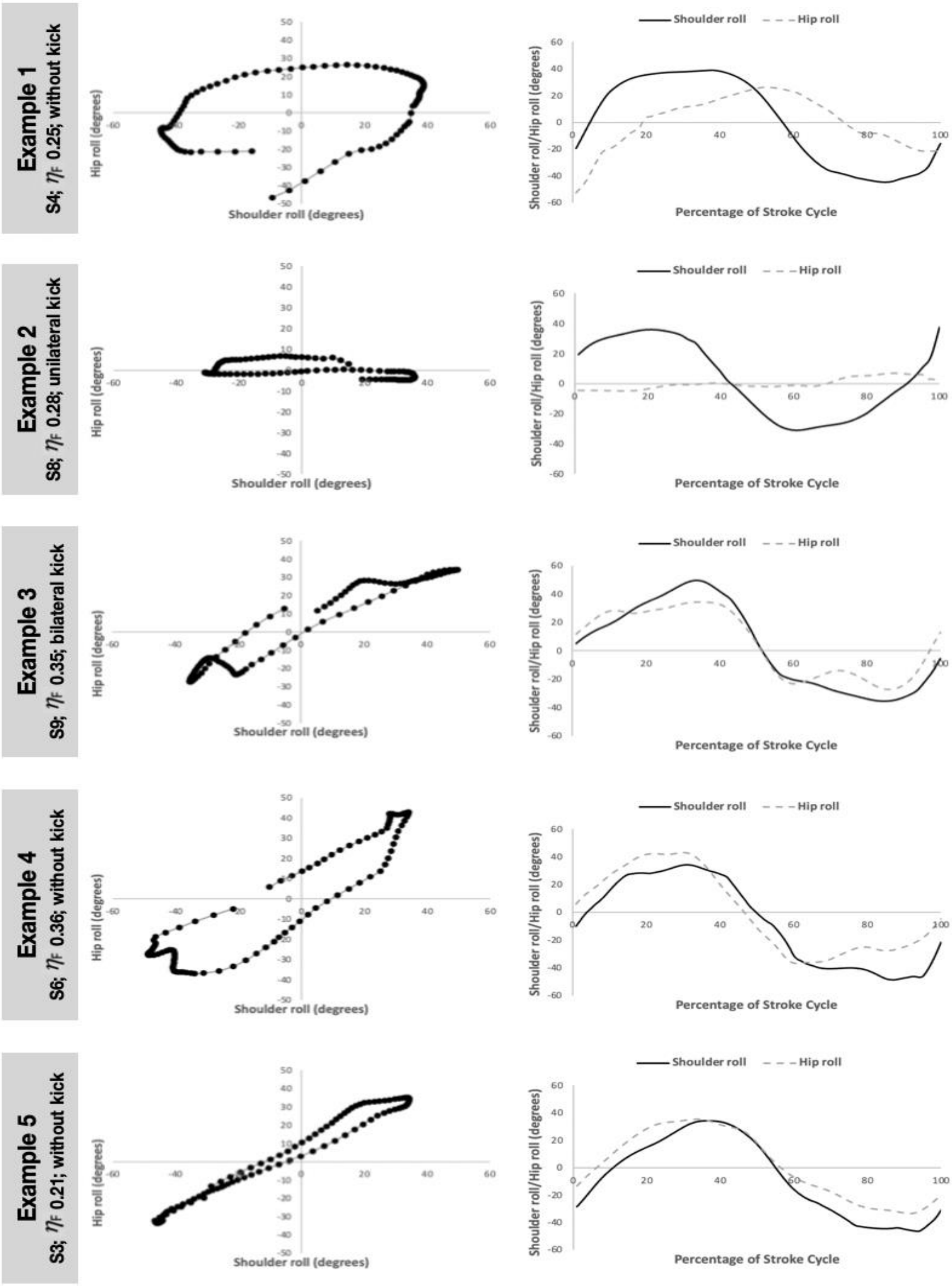


Figure 6.4: Five examples of angle-angle plots of shoulder roll and hip roll for one front crawl stroke cycle (left) and their corresponding shoulder roll and hip roll patterns over a full stroke cycle (right) from swimmers with central motor and neuromuscular impairment. Health condition of each example: 1) complete T8 spinal cord injury; 2) cerebral palsy; 3) neuromuscular disorder; 4) cerebral palsy with polyneuropathy of lower limbs; and 5) incomplete C5 spinal cord injury.

6.4 DISCUSSION

The aim of this study was to quantify front crawl body roll characteristics in a group of swimmers with CMNI. Compared to non-disabled swimmers, CMNI swimmers exhibited lower shoulder roll range, higher hip roll range, and lower torso twist. No association was found between S class and any of the body roll kinematics. None of the body roll variables were significantly different between performance-derived arm-impairment and leg-impairment sub-groups. However, there was a clear trend towards a lower range of shoulder roll in swimmers with higher Froude efficiency values. Swimmers with CMNI have varied roll profiles that suit their individual constraints in the water. It was hypothesised that CMNI swimmers display atypical body roll characteristics that differ from those of non-disabled swimmers. The hypothesis was thus accepted.

6.4.1 Non-disabled versus CMNI swimmers

CMNI swimmers had significantly lower stroke frequencies than the non-disabled swimmers yet did not manage to roll their shoulders further in their longer stroke cycle duration. When sprinting, swimmers need to increase the torque if they are to produce the same amount of shoulder roll as they do at 400 m pace (Andersen et al., 2020). Perhaps even with the maximum swim effort and longer stroke cycle duration, CMNI swimmers were less effective at using hydrodynamic forces on their upper limbs to increase the torque to achieve the same amount of shoulder roll as non-disabled group. It seems likely from the results of study 2 that swimmers with CMNI have reduced upper limb effectiveness, such that the work they do with their upper limbs is not transferred effectively into propulsion generation. It follows that this reduced effectiveness in generating hydrodynamic forces may also impact their ability to generate normal shoulder roll kinematics. However, if the CMNI swimmers did roll their shoulders more or to the same extent as the non-disabled group, they would likely encounter difficulties in balancing their body after rolling their shoulders due to the absence of leg kick. It may therefore be a deliberate choice not to roll their shoulders as much in order to prioritise stability of the body position in the water. Either way, the consequences of them rolling their shoulder less may contribute to an increase in drag because of the increase in projected frontal area against the water (Castro et al., 2003) and a decrease in stroke length due to a reduced glide/stretch of the arm in front of the head.

Most of the CMNI swimmers (n = 19) used only their upper limbs when swimming. This would reduce the options available to these swimmers for generating internal and external torques to drive their body roll. With a weak or absent leg kick, it may be that a lack of hydrodynamic forces on the legs, or absent internal torques acting on the lower trunk, allowed the hips to continue to roll further passively than they would have if a kicking action had been present. This would explain why the CMNI swimmers' hips rolled more than their non-disabled counterparts did. This also accords with the observation in a previous study that a strong and effective leg kick contributes to a reduction in hip roll (Andersen et al., 2020).

Although the shoulder and hip roll asymmetries were not significantly different between the groups, there was a clear trend for the CMNI group presenting higher asymmetry. The angle-angle plot examples (see Figure 6.4) illustrate that it is clearly a challenge for this impairment group to produce the same roll pattern to both sides. Their body roll asymmetry may be due to two factors: (i) hemiplegia or (ii) weak/full absence of one lower limb. However, Psycharakis and Sanders (2008) and (Gonjo et al., 2019) both concluded that no relationship existed between swimming speed and the magnitude of roll asymmetries. There was no identical body roll pattern within the

CMNI group; they presented a wide variety of roll kinematics likely dictated by the constraints of their impairments.

The substantially lower torso twist found in the CMNI group was owing to their considerably lower shoulder roll and greater hip roll than non-disabled swimmers. It is thus not surprising that their torso twist was lower. Andersen et al. (2020) reported that torso twist was greater at sprint pace than at 400 m pace and suggested that demands on the torso muscles are likely to be higher at faster swimming speeds. Even though CMNI swimmers performed front crawl at a fast race pace, they did not twist their torso to the same magnitude as non-disabled swimmers did. This could be due to several factors, but for some of the Para swimmers, this is likely due to weaker torso muscles and/or poorer control of torso muscles compared to non-disabled swimmers. Moreover, Hyodo et al. (2023) suggested that an increase in torso twist is associated with an increase in swimming speed. It can be speculated that the reason why the swimming speed in CMNI population is limited may be due partly to a reduced functionality of their torso muscles. Further investigation is required to address the role of torso twist in CMNI front crawl swimming.

Regarding the coordination of the hip and shoulder roll, non-disabled swimmers generally had a positive roll phase lag as their hips reached maximum roll before the shoulders did (on average 8.7% on the greatest shoulder roll side and 6.8% on the least shoulder roll side). Similarly, CMNI swimmers generally have both peaks led by hips with roll phase lags of 4.0% and 1.0% to the greatest and least shoulder roll sides, respectively. Although the roll phase lag values were not significantly different between groups, non-disabled swimmers were on average 2–6 times greater than those of CMNI group, indicating that non-disabled swimmers may have stronger oblique muscle groups than the CMNI swimmers to actively roll their hips (Andersen et al., 2021). This suggestion is supported by the angle-angle plot examples from non-disabled and CMNI swimmers. With complete torso control and a functional leg kick, the non-disabled swimmer seems to have a more symmetrical roll profile and his shoulder roll and hip roll may be more independent from each other than the roll profiles of the CMNI group. The inconsistency in CMNI angle-angle plots may be due in part to different levels of impaired torso muscles. However, Psycharakis and Sanders (2008) pointed out that no relationship was evident between swimming performance and timing differences in non-disabled swimmers. It is likely that a swimmer's coordination pattern is optimised to accommodate their individual characteristics and that no single body roll profile is the ideal for all swimmers.

Interestingly, none of the CMNI swimmers in this study exhibited similar combinations of shoulder roll and hip roll to those of the non-disabled swimmers. The CMNI group had 2–5 times more variability in their body roll metrics than the non-disabled group which reflects the heterogenous nature of the group that comprised a range of impairment types and severities. These differences in motor pattern could be interpreted as their adaptation to the activity limitation while trying to complete a task (Latash and Anson, 1996). With reduced arm effectiveness and a weak or absent leg kick, the roll profiles of CMNI swimmers seem to be functional in ways that suit their impairment type, severity and impairment location to perform front crawl techniques. Differences in both internal and external torques about the swimmer's body roll (longitudinal) axis could have contributed to the differences in body roll kinematics observed in CMNI swimmers. Although this impairment group was able to execute a body roll action in front crawl swimming, the amplitude and coordination of their body roll may not have been optimal for generating propulsion and minimise drag, and consequently would impact on their swimming speed.

6.4.2 Effect of performance-derived impairment severity

No association was found between swimming-specific impairment level (sport class) and any of the body roll variables. Since each sport class should comprise swimmers with similar levels of activity limitation, it could be expected that swimmers within a single class would have similar roll profiles. However, within sports classes, CMNI swimmers have a wide range of shoulder roll and hip roll combinations which may consequently affect their swimming speed differently. As the nature of CMNI encompasses various impairment type and severity, exploring the effect of performance-derived arm impairment and leg impairment on body roll kinematics may provide some insights of how CMNI swimmers roll their body in the water.

Swimming speed, stroke length and stroke frequency all differed significantly between the performance-derived arm-impairment sub-groups, which might be expected given that the groups were formed on the basis of their Froude efficiencies. Although body roll kinematics were not significantly different between performance-derived arm-impairment sub-groups, there was a clear trend towards a lower range of shoulder roll in swimmers with a higher Froude efficiency. A possible explanation for this might be that the hydrodynamic and internal muscle forces available to limit range of shoulder roll will be reduced in swimmers with a lower Froude efficiency. This finding is consistent with Psycharakis and Sanders (2008) who reported that faster swimmers tended to roll their shoulders less than slower swimmers during a 200 m swim. Moreover, the severe performance-derived arm impairment group actually had similar shoulder roll values to the non-disabled swimmers. However, it should be noted that their stroke frequency was considerably lower, so they took longer to achieve this similar shoulder roll range.

Body roll variables did not differ significantly between the performance-derived leg-impairment sub-groups. However, it is noteworthy that $LI_{unilateral}$ swimmers had ~20° greater shoulder roll range than those with no kick ($LI_{without\ kick}$) or a two leg kick ($LI_{bilateral}$). This observed trend toward greater shoulder roll may be a strategy employed by the $LI_{unilateral}$ group to balance the asymmetries caused by the lower limbs. Surprisingly, hip roll range was higher in $LI_{bilateral}$ than in the other two groups. This outcome contradicts a previous finding in non-disabled swimmers that a strong leg kick reduces hip roll range (Andersen et al., 2020). However, the two swimmers in $LI_{bilateral}$ group had different impairments. One swimmer with hip roll range 62° had spina bifida and the other, with hip roll range 114°, had diminished muscle strength and impaired hip range of motion. This may explain why the latter swimmer had excessive hip roll range despite having two functional legs.

One unanticipated finding for the CMNI swimmers, not observed in non-disabled swimmers in this study or in previous ones, was a positive association between stroke length and hip roll range in CMNI swimmers. This is likely due to the mechanisms driving the hip roll being completely different for swimmers with or without an impairment. The hip roll of the non-disabled group was mainly controlled by the leg kick, whereas the hip roll of the CMNI group was passively following the upper limb motion. Range of torso twist seems to be lowest in the swimmers with the least severe performance-derived arm and leg impairments (in AL_{mild} and $LI_{bilateral}$). It has been suggested that large torso twist may increase the swimmer's frontal area and consequently lead to more active drag during front crawl (Cappaert et al., 1995; Psycharakis and Sanders, 2008). Considering more impaired CMNI swimmers create higher passive and active drag when swimming (Payton et al., 2020), their large torso twist may indirectly contribute to one of the reasons why they have lower swimming speed.

Angle-angle plot examples have evidenced that each swimmer exhibited different roll profiles which likely adjust to their constraints caused by CMNI. Whilst shoulder roll and hip roll typically peaked at around 35% and 75% of the stroke cycle, example 1 had his hip roll peak at 55% and 100% of the stroke cycle. These delayed peaks may indicate this swimmer did not have active control of his hip rotation and that the hips were only rotating passively because of the shoulders. A complete T8 spinal cord injury signifies normal upper limb function, affected trunk muscles and paraplegia (Kirshblum et al., 2011). Thus, this swimmer's constraints are reflected in his body roll profile. Although example 5 had a higher injury on the spinal cord than example 1, she was able to roll her hips actively using her trunk muscles as an incomplete C5 spinal cord injury signifies partial paralysis of wrists, trunk and legs (Kirshblum et al., 2011).

One interesting observation is that the roll profile in example 2 looks completely different from the others. While it was expected to see an asymmetrical hip roll due to this swimmer's unilateral kick, he was keeping his pelvis parallel to the water surface and barely generating any hip roll. Examples 3 to 5 had similar shoulder roll and hip roll patterns over a stroke cycle despite their different impairment types. The space within the angle-angle plots (the area in the middle of the curve) relates to the asymmetry of the torso twist between when the swimmers rolled clockwise and anticlockwise, with bigger space representing greater asymmetry in the torso twist.

6.4.3 Limitations

An uncontrolled factor and therefore a confounding variable in this study was the participants' stroke frequency. As stroke frequency is inversely related to body roll (Yanai, 2003), the higher a swimmer's stroke frequency the lower their body roll. Another limitation was the sample size of the three LI groups (n = 19, 6 and 2) which was dictated by the number of functional leg kicks used. This precluded the use of statistical analysis to assess the differences between severity groups. Thus, the relationships between body roll kinematics and leg impairment severity are still unclear. Further work needs to be done to: (i) recruit more CMNI and non-disabled swimmers to provide a better understanding of the impact of their impairment on body roll kinematics; (ii) establish whether range of torso twist affects active drag in CMNI swimmers; and (iii) investigate the contribution of different torques to the body roll in this population in order to explain their roll profiles.

6.5 CONCLUSION

This study has quantified body roll kinematics in swimmers with CMNI and established the differences in these variables from non-disabled swimmers. CMNI swimmers showed significantly lower shoulder roll and higher hip roll than non-disabled swimmers likely due to their reduced arm effectiveness and a weak or absent leg kick. Atypical body roll in this impairment group may hinder their ability to generate propulsion and minimise drag, and consequently limit swimming speed. Within the CMNI group, those who have severe arm impairment may demonstrate greater range of shoulder roll as there is lack of internal and external torques to limit the shoulders' rolling. Moreover, there was no identical body roll pattern in this population, their roll profiles varied based on the combination of a swimmer's impairment type and severity and impairment location. It seems likely their body roll profiles reflect their individual constraints in the water.

CHAPTER 7

Study 4: Froude efficiency, intra-cyclic speed fluctuation and index of coordination in front crawl swimmers with central motor and neuromuscular impairment

7.1 INTRODUCTION

Para swimming is one of the most popular and inclusive Para sports, allowing individuals with a range of physical, visual and intellectual impairments to compete regionally, nationally and internationally, including on the biggest stage, the Paralympics. To provide fair competition, a functional classification system groups swimmers with eligible physical impairments into ten sport classes using physical bench tests and a water-based technical assessment (World Para Swimming, 2018). Swimmers with different health conditions (e.g., cerebral palsy, amputee, spinal cord injury) may compete within the same class if deemed to have an equivalent level of activity limitation. As the Paralympic Movement has matured, the validity of the measures and procedures used in the functional classification system have come under increasing scrutiny (Tweedy and Vanlandewijck, 2011). Studies have demonstrated that the current Para swimming classification system fails to differentiate performance clearly between adjacent classes and may disadvantage swimmers with certain impairment types within a class (Oh et al., 2013; Payton et al., 2020). The system relies heavily on the subjective opinion of clinical experts using ordinal-scale measures, rather than on empirical evidence (Oh et al., 2013), so in 2009 the International Paralympic Committee mandated the development of new evidence-based classification systems across all Para sports. To achieve this in Para swimming it is necessary to establish the effect of impairment type and severity on the determinants of swimming performance (Tweedy et al., 2016).

Swimmers with central motor and neuromuscular impairment (CMNI) are challenging to classify objectively as many of the quantitative measurements required for evidence-based classification are yet to be explored (Tweedy and Vanlandewijck, 2011). Motor coordination is an ability to activate multiple joints and muscles to execute accurate, smooth and efficient movement (Shumway-Cook and Woollacott, 2014). Individuals with CMNI are defined as having a health condition of traumatic brain injury, cerebral palsy, spinal cord injury, or other neuromuscular disorder that causes awkward, extraneous, uneven, or inaccurate movement characteristics (Schmitz and O'sullivan, 2013). The activity limitations that these individuals exhibit can vary considerably according to the type, the severity, or the location of the central nervous system pathology. Individuals with CMNI performing land-based sports present impaired range of motion (Connick et al., 2015), reduced muscle strength (Beckman et al., 2016) and poor motor coordination (Roldán et al., 2017). Knowledge of the challenges CMNI swimmers experience in the water is limited (Feitosa et al., 2019; Payton et al., 2020; Santos et al., 2020a; Satkunskienė et al., 2005). As efficient front crawl requires a series of coordinated movements from multiple body parts to propel the body forward in the water, with rhythmic and synchronized motions, it can be speculated that CMNI will constrain swimming performance.

A swimmer's speed is largely dependent on their capacity to maximise propulsion and minimise drag forces from the water (Toussaint and Beek, 1992). Front crawl is the fastest swimming technique in which 85% of total propulsion is produced by the upper limbs (Toussaint and Beek, 1992). As such, optimum coordination between the upper limbs is key to maximising propulsion. This coordination is often quantified using the index of coordination (*IdC*) which denotes the lag time between the propulsive actions of the left and right upper limb (Chollet et al., 2000). A swimmer's *IdC* can be categorised as (i) catch-up: a time gap exists between propulsion from the two limbs (*IdC* < 0%); (ii) opposition: one limb commences propulsion as the opposite limb ends its propulsion (*IdC* = 0%); and (iii) superposition: there is overlap between propulsion from the two limbs (*IdC* > 0%). Typically, faster swimmers present greater *IdC* values (higher propulsive continuity) than less proficient swimmers at 50 m, 100 m and 800 m paces (Chollet et al., 2000) as greater *IdC* had shown to be associated with intra-cyclic speed fluctuation and in turn energy cost (Barbosa et al., 2006). Seifert et al. (2004) reported a mean *IdC* of -1.0 ± 4.5% for non-disabled elite swimmers at their 100 m pace. At the same relative pace, a group of swimmers, with physical impairments varying in type and severity, recorded a mean *IdC* of 4.7 ± 12.0% with some swimmers exhibiting extreme catch-up or superposition timing (Satkunskienė et al., 2005).

During an upper limb cycle, swimmers do not progress at a constant speed as variations in propulsive and resistive forces cause their centre of mass speed to fluctuate (Zamparo et al., 2020). Intra-cyclic speed fluctuation defines how much a swimmer’s speed varies within a cycle and has been proposed as an indicator of swimming efficiency in non-disabled swimmers (Alberty et al., 2005; Barbosa et al., 2006). Many studies assess the intra-cyclic speed fluctuation of a fixed point on the body using a ‘velocimeter’ (Alberty et al., 2005; Schnitzler et al., 2010). This approach can misrepresent the variation of the swimmer’s mass centre speed (Psycharakis and Sanders, 2009) so three-dimensional motion analysis is advocated as a more accurate and valid method to assess intra-cyclic speed fluctuation (Psycharakis et al., 2010). Intra-cyclic speed fluctuation is usually reported either as the coefficient of variation of the speed ($ICSF_{CV}$) (Barbosa et al., 2006; Matsuda et al., 2014; Schnitzler et al., 2010), or as the intra-cyclic speed range expressed as a percentage of mean speed in the cycle ($ICSF_{\%}$) (O'Dowd et al., 2023; Payton and Wilcox, 2006; Psycharakis et al., 2010). Intra-cyclic speed fluctuation values ranging from 6% (Matsuda et al., 2014) to 24% (Figueiredo et al., 2013a) have been reported for non-disabled front crawl swimming, with a wider range of values, 5% (O'Dowd et al., 2023) to 36% (Feitosa et al., 2019), being reported for swimmers with physical impairments. This high variability of intra-cyclic speed fluctuation values in the literature is likely due to differences in factors such as test speed, participant skill level, presence and level of physical impairment, data capture method and computational procedures.

Another important performance determinant associated with energy cost in front crawl is Froude efficiency (η_F) (Gonjo et al., 2018; O'Dowd et al., 2023). Froude efficiency represents the fraction of the external mechanical power generated by the swimmer that is used to overcome hydrodynamic drag (Zamparo et al., 2020). Due to the technical complexities of measuring a swimmers' mechanical power output and hydrodynamic drag, various models have been proposed to provide indirect estimates of Froude efficiency. These models generally require kinematic data on the swimmer's upper limb and a measure of their swimming speed (Gonjo et al., 2018). The simplest models estimate hand speed indirectly from two-dimensional motion analysis or assume the swimmer's intra-cyclic speed and angular velocity of the upper limbs are constant (Zamparo et al., 2005). More sophisticated models utilise three-dimensional analysis of the upper limb and the swimmer's mass centre speed (see Zamparo et al. (2020) for a detailed discussion of these methods).

In non-disabled front crawl swimming, Froude efficiency values range from 0.20 to 0.63 (Toussaint, 1990; Zamparo et al., 2020), with faster swimmers having higher values than slower swimmers (Ribeiro et al., 2017). In a diverse group of Para swimmers comprising seven amputees and four with a CMNI, Froude efficiency ranged from ~0.20–0.39 with swimmers in the less impaired classes tending to have a higher Froude efficiency than those in the more impaired classes (Feitosa et al., 2019). A recent study of unilateral forearm amputees reported a mean Froude efficiency of 0.37 at 400 m pace, lower than comparable values for non-disabled swimmers (O'Dowd et al., 2023). These studies highlight that Froude efficiency may be a valid measure of activity limitation in Para swimmers and a useful tool for comparing swimmers with different types and severity of physical impairment.

Intra-cyclic speed fluctuation, index of coordination and Froude efficiency have not been assessed collectively in a large group of front crawl swimmers with CMNI but studies involving groups of swimmers with a range of impairment types have shown that: (i) physically impaired swimmers have a lower index of coordination (Feitosa et al., 2019; Santos et a., 2020a) and higher intra-cyclic speed fluctuation (Junior et al., 2018) than non-disabled swimmers, (ii) more impaired swimmers present higher intra-cyclic speed fluctuation and lower Froude efficiency than less impaired swimmers (Feitosa et al., 2019), (iii) no association exists between index of coordination and impairment severity (Satkunskienė et al., 2005). Swimmers with CMNI create higher active drag and lower propulsive force than non-disabled swimmers during front crawl (Hogarth et al., 2020; Payton et al., 2020). Given that intra-cyclic speed fluctuation and Froude efficiency are both influenced by these hydrodynamic forces, and index of coordination reflects the temporal sequencing of propulsion from the upper limbs, it can be speculated that CMNI will cause poorer Froude efficiency, excessive fluctuation of the swimmer's speed, and atypical coordination between the upper limbs.

New knowledge of how CMNI affects the determinants of front crawl swimmer's performance would contribute to the development of an evidence-based classification system for World Para Swimming. Therefore, the aims of this study are to: (i) compare index of coordination, intra-cyclic speed fluctuation and Froude efficiency between non-disabled swimmers and those with CMNI, (ii) determine the impact of CMNI severity (sport class) on intra-cyclic speed fluctuation and Froude efficiency, and (iii) assess the effect of performance level (elite and sub-elite) in those with CMNI on index of coordination, intra-cyclic speed fluctuation and Froude efficiency. It is hypothesised that: (i) intra-cyclic speed fluctuation and Froude efficiency differ between non-disabled swimmers and swimmers with CMNI, (ii) CMNI severity is associated with Froude efficiency and intra-cyclic speed fluctuation, (iii) elite and sub-elite CMNI swimmers differ in their index of coordination, intra-cyclic speed fluctuation and Froude efficiency, and (iv) associations exist between index of coordination, intra-cyclic speed fluctuation and Froude efficiency.

7.2 METHOD

7.2.1 Participants

Please refer to chapter 4 – General Methods – for participant information.

Para swimmers were examined as a pooled group and as two subgroups: elite (n = 15) and sub-elite (n = 12). They were categorised as elite if they had competed in a Paralympic Games and their best front crawl race time, expressed as a percentage of the world record time for their sport class, was 75% or higher.

7.2.2 Data collection protocol

Please refer to chapter 4 – General Methods – for equipment details, pool calibration, video capture, video digitising, and data processing methods.

7.2.3 Data analysis and definition of variables

The following variables were calculated: (i) *mean swimming speed* (v_{MEAN}): mean velocity of the whole-body mass centre in the y-direction, (ii) *stroke frequency* (*SF*): reciprocal of the upper limb cycle multiplied by 60, (iii) *stroke length* (*SL*): displacement of whole-body mass centre in the y-direction during an upper limb cycle, (iv) *index of coordination* (*IdC*): quantified as the lag time between left and right propulsive phases, which was from the beginning of the backward movement relative to the water until the wrist exit from the water, and expressed as a percentage of duration of a complete stroke cycle (Figueiredo et al., 2013a). *IdC* was the mean of *IdC* left and *IdC* right, (v) *maximum speed* (v_{MAX}): highest instantaneous velocity in the stroke cycle, (vi) *minimum speed* (v_{MIN}): lowest instantaneous velocity in the stroke cycle, (vii) *relative maximum speed* ($v_{MAX\%}$): v_{MAX} / v_{MEAN} × 100, (viii) *relative minimum speed* ($v_{MIN\%}$): v_{MIN} / v_{MEAN} × 100, (ix) *absolute intra-cyclic speed fluctuation* ($ICSF_{ABS}$): v_{MAX}-v_{MIN}, (x) relative intra-cyclic speed fluctuation ($ICSF_{\%}$): $[(v_{MAX}-v_{MIN})/v_{MEAN}] \times 100$, (xi) *coefficient of variation of intra-cyclic speed fluctuation* ($ICSF_{CV}$): v_{SD} / v_{MEAN} × 100 where v_{SD} is the standard deviation of the v_{MEAN}, and (xii) *Froude efficiency* (η_F): v_{MEAN} / (v_{WRIST_SUM}) where v_{WRIST_SUM} is the mean 3D speed of both wrists during their respective underwater phases of the stroke cycle (Figueiredo et al., 2013a).

7.2.4 Statistical Analysis

All data were checked for parametricity using the Shapiro-Wilk test and some data were not normally distributed. Mann-Whitney U tests were used to identify where dependent variables were significantly different between non-disabled and CMNI swimmers. Within the CMNI group, independent t-tests were used to assess the differences between the elite and sub-elite groups. Strength of associations between impairment severity (sport class) and each dependent variable were assessed using Kendall's tau coefficients, which were interpreted as ≤ .40 = small, .41 to .60 = moderate, .61 to .79 = large and ≥ .80 = very large (Mukaka, 2012). Strength of associations between index of coordination, intra-cyclic speed fluctuation and Froude efficiency were assessed using Pearson correlation coefficient. The threshold for statistical significance was set at $p < .05$ and defined as weak (< 0.3), moderate (0.3-0.6), or strong (> 0.6). All analyses were conducted using IBM SPSS Statistics 28 software and statistical significance was set at $p <.05$.

7.3 RESULTS

Mean and standard deviation of discrete variables are shown in Table 7.1. Data are presented for non-disabled swimmers, for CMNI swimmers and for elite and sub-elite CMNI performance groups. Mann-Whitney U tests revealed that all variables were significantly different between non-disabled and CMNI swimmers except *IdC* and $ICSF_{ABS}$. On the other hand, variables swimming speed, v_{MAX}, v_{MIN} and $ICSF_{ABS}$ ($p < .05$) were significantly different between the elite and sub-elite groups; all other variables including Froude efficiency ($p = .073$) were not.

Table 7.1: Front crawl variables for non-disabled swimmers (n = 13) and swimmers with central motor and neuromuscular impairment, presented as a pooled CMNI group (n = 27), an elite (n = 15) and a sub-elite (n = 12) performance group (mean ± SD). [a] represents a significant difference between non-disabled and CMNI groups; [b] represents a significant difference between the elite and sub-elite groups.

	Non-disabled group (n=13)	**CMNI group (n=27)**	**Elite group (n=15)**	**Sub-elite group (n=12)**
v_{MEAN} ($m \cdot s^{-1}$)	1.83 ± 0.13	1.03 ± 0.30 [a]	1.15 ± 0.29	0.87 ± 0.25 [b]
SF ($stroke \cdot min^{-1}$)	52.2 ± 4.9	41.8 ± 9.2 [a]	44.2 ± 9.2	38.9 ± 8.6
SL (m)	2.12 ± 0.14	1.47 ± 0.32 [a]	1.56 ± 0.29	1.37 ± 0.34
IdC (%)	−13 ± 3	−13 ± 8	−13 ± 6	−13 ± 10
v_{MAX} ($m \cdot s^{-1}$)	2.01 ± 0.15	1.17 ± 0.33 [a]	1.31 ± 0.32	1.00 ± 0.27 [b]
v_{MIN} ($m \cdot s^{-1}$)	1.66 ± 1.33	0.86 ± 0.28 [a]	0.96 ± 0.28	0.73 ± 0.24 [b]
$ICSF_{ABS}$ ($m \cdot s^{-1}$)	0.35 ± 0.05	0.32 ± 0.11	0.36 ± 0.11	0.27 ± 0.08 [b]
$v_{MAX\%}$ (%)	110 ± 2	115 ± 5 [a]	115 ± 5	115 ± 5
$v_{MIN\%}$ (%)	91 ± 2	83 ± 6 [a]	82 ± 7	83 ± 6
$ICSF_{\%}$ (%)	19 ± 3	32 ± 10 [a]	32 ± 11	33 ± 10
$ICSF_{CV}$ (%)	4 ± 1	8 ± 2 [a]	8 ± 2	8 ± 2
η_F	0.35 ± 0.04	0.29 ± 0.07 [a]	0.31 ± 0.06	0.27 ± 0.06

Figure 7.1 shows the speed-time histories over a full stroke cycle for the non-disabled and CMNI swimmers. What can be clearly seen in this figure is the speed differences between swimmers with or without an impairment. Non-disabled swimmers' speed curve was less fluctuated and with lower standard deviation than CMNI swimmers'. The speed curves for elite and sub-elite CMNI performance groups are shown in Figure 7.2. Although high standard deviation exists in both speed curves, there is a significant speed difference (*p* < .05; Table 7.1) between the two performance groups.

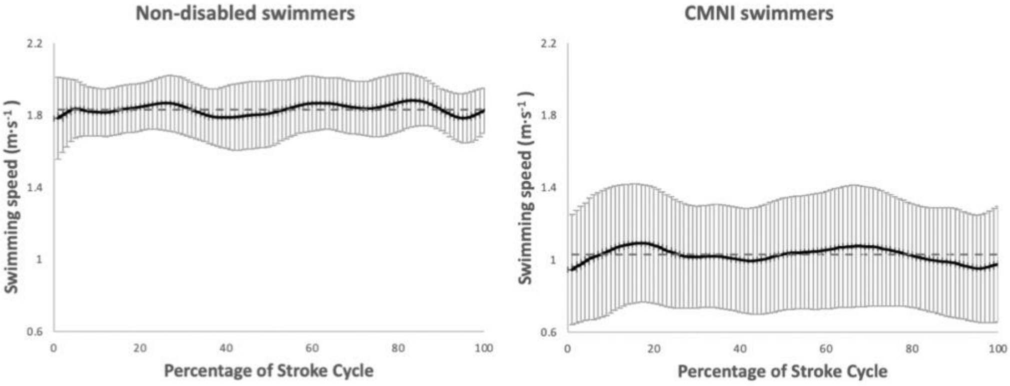


Figure 7.1: Mean value of centre of mass speed curve within one stroke cycle for non-disabled swimmers (left; n = 13) and swimmers with central motor and neuromuscular impairment (right; n = 27). The dashed line denotes the group's mean swimming speed for the stroke cycle.

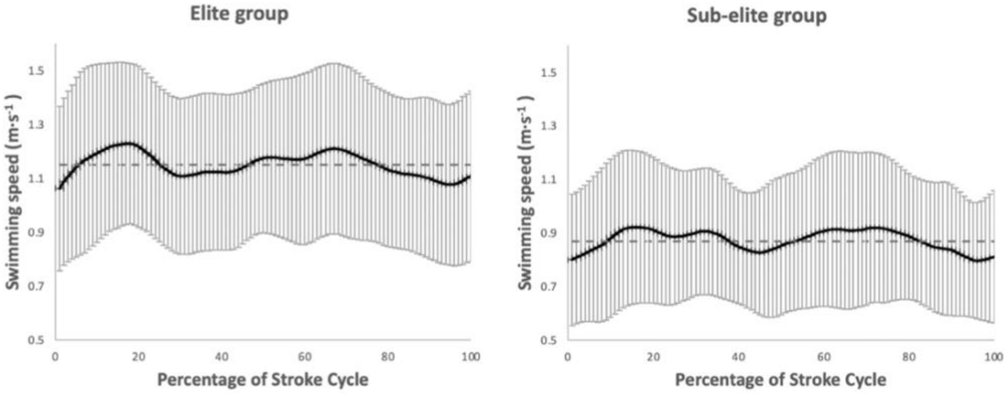


Figure 7.2: Mean value of centre of mass speed curve within one stroke cycle for an elite (left; n = 15) and a sub-elite (right; n = 12) performance group. The dashed line denotes the group's mean swimming speed for the stroke cycle.

7.3.1 Effect of impairment severity (sport class) on index of coordination, intra-cyclic speed fluctuation and Froude efficiency

A moderate negative association was found between *ICSF*$_{\%}$ and sport class (τ = - .33, *p* < .05; Figure 7.3). No significant association was found between *ICSF*$_{\mathrm{CV}}$ and sport class (*p* = .057) or between *IdC* and sport class (*p* > .05). A moderate positive correlation was found between Froude efficiency and sport class (τ = .42, *p* < .01; Figure 7.3). Moreover, sport class was significantly related to swimming speed and stroke length (τ = .40 to .43, *p* < .01).

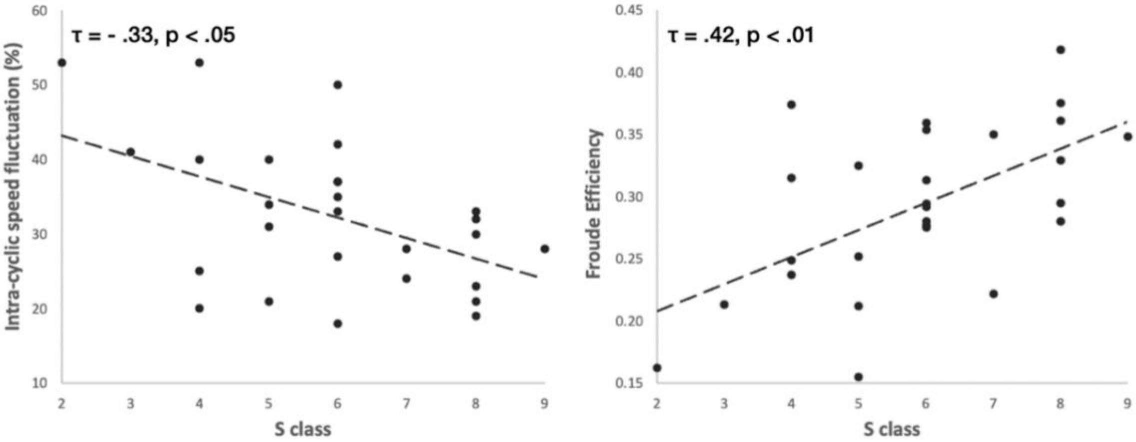


Figure 7.3: Scatterplots of Intra-cyclic speed fluctuation (left) and Froude efficiency (right) versus Sports Class for central motor and neuromuscular impaired swimmers in S2–S9.

7.3.2 Associations between swimming speed, stroke frequency, stroke length, index of coordination, intra-cyclic speed fluctuation and Froude efficiency in CMNI swimmers

Moderate negative associations were found between swimming speed and *ICSF*$_{\%}$ and between swimming speed and *ICSF*$_{\mathrm{CV}}$ (*r* = - .51 to - .56, *p* < .01). A strong positive association was found between swimming speed and Froude efficiency (*r* = .71, *p* < .001). No relationship existed between swimming speed and *IdC* (*p* > .05). Stroke frequency had strong negative correlations with $ICSF_{\%}$ and $ICSF_{CV}$ (r = - .64 to - .70, p < .001). Stroke length had strong negative correlations with *IdC* (r = - .61, p < .001) and strong positive correlations with Froude efficiency (r = .80, p < .001). $ICSF_{\%}$ was strongly related to $ICSF_{CV}$ (r = .99, p < .001). Although Froude efficiency was not related to $ICSF_{\%}$ or $ICSF_{CV}$ (p > .05), Froude efficiency had a strong negative association with *IdC* (r = - .62, p < .001).

7.4 DISCUSSION

This study is the first to investigate front crawl determinants in a group of swimmers with CMNI. CMNI swimmers exhibited higher $ICSF_{\%}$ and $ICSF_{CV}$, and lower swimming speed, v_{MAX}, v_{MIN}, $v_{MIN\%}$ and Froude efficiency during front crawl swimming, when compared to highly trained non-disabled swimmers. Impairment severity (sport class) was strongly associated with $ICSF_{\%}$ and Froude efficiency in swimmers with CMNI. That is, as the severity of swimming-specific impairment decreased, $ICSF_{\%}$ decreased and Froude efficiency increased. Within the impaired group, *IdC*, intra-cyclic speed fluctuation and Froude efficiency did not differ significantly between the elite and sub-elite performance groups. Nevertheless, there was a trend toward a higher Froude efficiency in the CMNI elite group. As such, the study's first three hypotheses were partially accepted.

7.4.1 Non-disabled versus CMNI swimmers

The finding of no difference in *IdC* between the groups contradicts previous studies which have suggested that swimmers with higher swimming speed show higher *IdC* values (Chollet et al., 2000; Seifert et al., 2010c). Accordingly, our non-disabled swimmers might be expected to have had higher *IdC*, indicating less catch-up coordination, than CMNI swimmers considering their swimming speed was considerably greater than the CMNI swimmers'. However, the non-disabled group were able to swim faster than the CMNI group while utilising the same upper limb catch-up mode, indicating that they may produce greater propulsion compared to the CMNI group. In addition, no association was found between swimming speed and *IdC* in this study which is consistent with Bideault et al. (2013) who proposed that upper limb coordination is rather an individualised adaptation than a pattern to replicate. Perhaps for CMNI swimmers to optimise how their upper limbs interact with the water requires them to adopt atypical upper limb coordination rather than the conventional model.

The non-disabled swimmers in this study had significantly lower intra-cyclic speed fluctuation ($ICSF_{\%}$) than the CMNI group (non-disabled: 19 ± 3%, CMNI: 32 ± 10%) and were also slightly lower on this measure compared to previous studies (both reported 22%) (Psycharakis et al., 2010; Psycharakis and Sanders, 2009). It is possible that these relatively low $ICSF_{\%}$ values are partly due to the presence of three Olympic Gold medallists in our non-disabled group and the superior ability of these swimmers to maintain a more constant speed. For the CMNI group, the greater speed fluctuation may be due to a weak or absent leg kick in these individuals. This is especially relevant in faster swimming where the legs contribute more to propulsion and may minimise the loss of intra-cyclic speed more effectively (Osborough et al., 2015). Additionally, stroke frequencies in CMNI swimmers were lower than in the non-disabled group. Negative associations were found between stroke frequency and intra-cyclic speed fluctuation, that is, lower stroke frequencies were associated with greater intra-cyclic speed fluctuation in CMNI swimmers. This finding supports a previous one for a group of physically impaired swimmers where stroke frequency was found to be inversely related to intra-cyclic speed fluctuation (Junior et al., 2018).

As anticipated, the two measures of intra-cyclic speed fluctuation ($ICSF_{\%}$, $ICSF_{CV}$) were strongly associated with each other, but $ICSF_{CV}$ values compared inconsistently with published values. Our non-disabled and CMNI swimmers had $ICSF_{CV}$ values of 4 ± 1% and 8 ± 2%, respectively. Previous values of 6–7% (Gonjo et al., 2018; Matsuda et al., 2014) and 14–22% (Figueiredo et al., 2013a; Schnitzler et al., 2010) have been found for non-disabled swimmers, 24% in a heterogeneous groups of Para swimmers (Feitosa et al., 2019; Santos et al., 2020a), and 5% in forearm-amputee swimmers (O'Dowd et al., 2023). These discrepancies are likely explained by differences in the body landmark used to measure speed (hip, whole body mass centre, head mass centre), calculation approaches, testing protocols, participants' performance levels, and the impairment types and severities examined. Given the concerns raised about some of the intra-cyclic speed fluctuation calculation methods (Gonjo et al., 2019), care should be taken when comparing findings and conclusions between studies.

As expected, CMNI swimmers had lower Froude efficiencies than non-disabled swimmers. However, our non-disabled swimmers had lower Froude efficiency (0.35 ± 0.04) than some values reported previously (0.40–0.42) in well-trained non-disabled swimmers (Figueiredo et al., 2013a; Gonjo et al., 2018; Gonjo et al., 2020). This result may be due to our non-disabled group swimming considerably faster than participants in previous studies. Froude efficiency is swimming speed dependent and decreases with increased swimming speed (Gonjo et al., 2020). The poor Froude efficiency in CMNI swimmers is likely due to their shorter stroke length compared to the non-disabled group as a strong positive association was found between stroke length and Froude efficiency in this study. Indeed, Zamparo et al. (2005) reported that higher Froude efficiencies are associated with longer stroke lengths. It was established in study 2 that the limited stroke length of the CMNI swimmers was likely due to their affected hand positions and restricted elbow extension at the beginning of the glide phase and at the end of the push phase. As such, these factors may hinder the propulsion and may indirectly affect Froude efficiency. In addition, their poor Froude efficiency can also be linked to the greater drag coefficients that are inevitable due to their poor body orientations, as reported in study 2.

7.4.2 Effect of impairment severity (sport class)

In this study, the majority of CMNI swimmers utilised a catch-up mode of *IdC* and arm coordination pattern was not associated with the impairment severity or with swimming speed. As such, *IdC* was not related to swimming-specific impairment levels in the CMNI population. Instead, the impairment location and the type of CMNI, rather than the severity, may dictate arm coordination pattern. Further work is needed to confirm whether CMNI type the impairment location have impact on their *IdC*.

Sport class had a moderate negative association with $ICSF_{\%}$ and a moderate positive association with Froude efficiency. That is, as impairment severity decreased (higher sport classes), $ICSF_{\%}$ decreased and Froude efficiency increased (improved). This provides some evidence that those swimmers in higher classes may coordinate their limbs in a more energy efficient manner than swimmers in lower classes, as both intra-cyclic speed fluctuation and Froude efficiency are associated with the energy cost (Gonjo et al., 2018). Hence, these two variables may be useful criteria to differentiate between severities of CMNI. One unanticipated finding was that no association existed between intra-cyclic speed fluctuation and Froude efficiency despite their shared relationship with energy cost (Gonjo et al., 2018) so it seems that these variables provide different insights into how impairment influences swimming performance. Additionally, since $ICSF_{\%}$ and $ICSF_{CV}$ were strongly related, not only $ICSF_{\%}$ can differentiate between CMNI severities, but also potentially $ICSF_{CV}$ as there was also a strong trend towards a lower $ICSF_{CV}$ in higher sport class (p = .057).

7.4.3 Effect of performance level (elite and sub-elite CMNI swimmers)

In this study, CMNI swimmers were categorised as either elite or sub-elite based on how their best race times compared to the relevant World Record for their sport class. It was expected that identifying the performance level may provide further insight into how CMNI affects front crawl swimming. The elite group was predicted to have a higher *IdC* and Froude efficiency, and a lower intra-cyclic speed fluctuation than the sub-elite group because these differences have previously been found in non-disabled swimmers (Ribeiro et al., 2017; Schnitzler et al., 2010).

The faster swimming speed of the elite group can be explained by their higher stroke frequency and longer stroke length compared to the sub-elite group, although neither of these variables differed significantly between groups. The elite group was faster than the sub-elite group by chance rather than by design. The less impaired, faster swimmers in the cohort tended to benchmark better against their respective World records, than the more impaired, slower swimmers did. There was a clear trend towards Froude efficiency being greater in the elite swimmers indicating that these swimmers were able to interact with the water more effectively and, potentially, swim with less energy cost compared to the sub-elite swimmers, despite some having a lower sport class than those in the sub-elite group. Therefore, Froude efficiency may be useful to differentiate between performance levels in swimmers with CMNI.

In contrast to previous studies (Chollet et al., 2000; Ribeiro et al., 2017; Schnitzler et al., 2010; Seifert et al., 2007a), however, no evidence of lower IdC was found in our elite group. Interestingly, only one study in the literature reported that *IdC* is not a predictor of front crawl performance (Matsuda et al., 2014). This discrepancy could be attributed to their two performance level groups exhibiting similar stroke frequencies and a not significant difference (only a tendency) in their personal best 100 m race time. Since the stroke frequency did not differ between our two performance level groups, it appears that stroke frequency is more connected to the IdC mode than performance level is (Potdevin et al., 2006; Seifert et al., 2007b).

Intra-cyclic speed fluctuation has been established as a strong indicator of skill level in non-disabled swimmers (Matsuda et al., 2014; Psycharakis et al., 2010; Schnitzler et al., 2010; Seifert et al., 2010b). No such effect of performance level on intra-cyclic speed fluctuation was found in our CMNI swimmers. This was anticipated given that the CMNI swimmers presented with various type and severities of impairment which masked any differences due to skill level.

7.4.4 Limitations

The main limitations of this study must be acknowledged. This study only tested intra-cyclic speed fluctuation, IdC and Froude efficiency at a single speed. It does not consider the effects of fatigue or how these front crawl performance determinants may change throughout a race distance trial (O'Dowd et al., 2023). A relatively simple mathematical model was used in this study to represent Froude efficiency, a complex concept. The mechanical power of the swimmer and their hydrodynamic resistance were not assessed. In addition, this model also neglects the effect of lower limbs (Figueiredo et al., 2011). For the majority of our participants this assumption is valid, but for a minority, the lower limbs may have some effect on the Froude efficiency.

Another factor may influence the differences in intra-cyclic speed fluctuation and Froude efficiency between CMNI and non-disabled groups was the male dominant sample size in non-disabled swimmers. Although no sex difference was evident for Froude efficiency and intra-cyclic speed fluctuation (Zamparo et al., 2020), non-disabled female swimmers were found to have less drag to overcome (Barbosa et al., 2013a; Manley and Atha, 2013; Schnitzler et al., 2008; Toussaint et al., 2000) and on average 25 N less mechanical power output (Morouço et al., 2015; Toussaint et al., 2000) compared to their male counterparts. Finally, there were mixed front crawl techniques (front crawl with bilateral kick, unilateral kick, or absence of kick) presented by the participants, the results cannot generalise each freestyle variation as the sample size for some techniques were too small.

7.5 CONCLUSION

Swimmers with CMNI have greater $ICSF_{\%}$ and $ICSF_{CV}$ and lower Froude efficiency than non-disabled swimmers, reflecting a reduced ability to utilise fluid forces effectively during front crawl swimming. No significant difference was found in *IdC* between CMNI and non-disabled swimmers. Impairment severity of CMNI had a moderate association with $ICSF_{\%}$ and Froude efficiency with less impaired swimmers exhibiting lower $ICSF_{\%}$ and higher Froude efficiency. Thus, these two variables may be useful metrics to help classify this population. The findings in this study suggest that CMNI may influence energy cost of swimming, with greater effects in those swimmers who are more severely impaired.

CHAPTER 8

Study 5: Kinematic characteristics of double-arm backstroke – a specialist freestyle technique Para swimmers with central motor and neuromuscular impairment employ in freestyle events

8.1 INTRODUCTION

To participate in World Para Swimming sanctioned competitions, athletes are obligated to meet the eligible impairment requirements and be internationally classified into an assigned sport Class (World Para swimming, 2023). Para swimming races are held in backstroke, breaststroke, butterfly, freestyle, individual medley and relay events, over varying distances. In freestyle events swimmers may employ any style, but front crawl is the most common stroke used as it is generally the fastest and most efficient competitive stroke of the four (Barbosa et al., 2010; Seifert et al., 2005). However, swimmers with central motor and neuromuscular impairment (CMNI), especially those with more severe level of impairment, may not be capable of performing a standard front crawl technique.

CMNI is an umbrella term for individuals with impaired muscle power, hypertonia, ataxia and athetosis resulting from health conditions such as cerebral palsy, traumatic brain injury or spinal cord injury (Payton et al., 2020). Due to the nature of CMNI, these swimmers may have significant variability in impairment type and severity (Hogarth et al., 2019a) ranging from mild impairment of single limb to severe impairment of the trunk and all four limbs. In chapters 4 and 5 it was established that CMNI swimmers employ five technique variations in freestyle events: front crawl with bilateral kick, front crawl with unilateral kick, front crawl without kick, backstroke without kick and double-arm backstroke without kick. The more impaired the swimmer (the lower the sport class), the lower the trunk and/or lower limb function.

Whilst the vision of the International Paralympic Committee is to “make an inclusive world through sport” (International Paralympic Committee: Constitution, 2020, p. 1), unfortunately it has excluded all the individual swimming events for athletes with the most severe impairments (S1/S2) at the Paris 2024 Paralympic Games due to the rule for event viability (Dutia and Tweedy, 2021). These authors reported that the barriers to participation in sports were greater in athletes with more severe impairments than those with less severe impairments. Consequently, there has been a decline in the number of swimming events within international competitions available to S1/S2 athletes in the past twenty years. Despite the importance of including these swimmers in Para swimming competition programmes and supporting their development, Para swimming research to date has focused almost exclusively on front crawl technique (Gonjo et al., 2019; Hogarth et al., 2019a; Payton et al., 2020) which is not a viable option for more severely impaired CMNI swimmers.

In non-disabled front crawl, the upper limbs contribute approximately 85% of the total propulsion (Toussaint and Beek, 1992). In contrast, swimmers with severe CMNI typically have limited or no lower limb function meaning that all propulsion must be produced by the upper limbs, whilst having possibly to overcome additional drag created by a poor body inclination. Findings from chapters 5 and 7 show that stroke length, body/thigh inclinations, intra-cyclic speed fluctuation and Froude efficiency can distinguish the severity of CMNI in front crawl technique. Hence it can be speculated that these performance determinants may also be relevant in double-arm backstroke. No study has yet explored the relationship between this specialist freestyle technique and swimming performance of severely impaired CMNI swimmers.

Studies have demonstrated the kinematic, kinetic and energetic differences between front crawl and backstroke, showing that backstroke has higher energy cost (Gonjo et al., 2018), lower Froude efficiency, more active drag and larger mean underwater volume of the body (Gonjo et al., 2020), than front crawl. As double-arm backstroke without kick involves a simultaneous non-propulsive over-water recovery phase of the upper limbs, it seems likely that this lack of continuous propulsion would result in a higher intra-cyclic speed fluctuation and a lower Froude efficiency, compared to front crawl and backstroke. From an energy cost perspective, there is no apparent reason for CMNI swimmers to race using double-arm backstroke rather than front crawl. The decision to adopt this supine technique may relate to challenges involved in taking a breath when swimming prone. More severely impaired CMNI swimmers may lack the strength, range of motion or coordination necessary to rotate their body to take a breath, as is required in front crawl. CMNI swimmers with absent leg kick or poor control of the trunk demonstrated difficulties in controlling body roll in front crawl (chapter 6). Body roll facilitates the breathing action in front crawl and backstroke (Payton et al., 1999). If these severely impaired swimmers were to use alternating upper limb movements, their abnormal body roll may not aid the breathing action when swimming prone and their dysfunctional lower limbs might not balance and stabilise their body in the water if swimming supine. As such, a simultaneous upper limb motion is probably more feasible for our CMNI swimmer to avoid excessive body motion. Moreover, their impairment may inhibit the ability to perform alternating upper limb cycles effectively, so these individuals opt to swim with simultaneous upper limb movements to optimise propulsion.

Insufficient biomechanics research has been conducted on the factors that limit performance of swimmers with severe CMNI. This study aims to establish the differences in the kinematics and Froude efficiency of swimmers with severe CMNI to those of highly trained non-disabled swimmers, when performing double-arm backstroke. It is hypothesised that: (i) swimmers with CMNI present different kinematics and lower Froude efficiency than non-disabled swimmers when performing double-arm backstroke; (ii) double-arm backstroke has a lower Froude efficiency and higher intra-cyclic speed fluctuation than other freestyle techniques used by non-disabled and CMNI swimmers.

8.2 METHOD

8.2.1 Participants

Three highly trained CMNI swimmers and eight non-disabled swimmers participated in the study (Table 8.1). For further details on the non-disabled swimmers, please refer to section 3.2. The three CMNI swimmers all had cerebral palsy, a common term used to describe a group of neuromusculoskeletal conditions characterised by motor dysfunction (Levitt and Addison, 2018). They may present different traits as cerebral palsy is a heterogeneous clinical syndrome due to non-progressive brain damage early in life rather than a single disorder (Aisen et al., 2011). Swimmers A and C were both diagnosed as spastic diplegic which is characterised by floppiness of the neck and trunk together with stiff spastic limbs due to the delay development in stabilisation of pelvic and shoulder girdles (Levitt and Addison, 2018).

Table 8.1: Participant age, sex, anthropometric characteristics, sport class, and health condition.

	CMNI swimmer (n=3)			Non-disabled swimmers (n=8)	
	A	B	C		
Sex	Female	Male	Male	Female (n=1)	Male (n=7)
Age (yrs)	33	34	33	22	23.3 ± 2.6
Height (cm)	147.5	165.0	166.3	192.5	186.9 ± 5.6
Body mass (kg)	48.4	72.0	65.0	93.5	84.2 ± 6.2
Sport class	S4	S3	S4		
Health condition	Cerebral Palsy (Spastic Diplegia) + Hypertonia	Cerebral Palsy	Cerebral Palsy (Spastic Diplegia) + Hypertonia		

8.2.2 Data collection protocol

After a warmup with self-selected volume and intensity, participants were instructed to perform 25 m double-arm backstroke trials at their 100 m pace from a push start. Participants typically completed two trials and were given at least 3 minutes rest between trials. The non-disabled group was instructed not to use their lower limbs during double-arm backstroke. As they were not familiar with this technique, they were checked on their ability to perform it and were required to repeat the trial if they did not comply. Please refer to chapter 4 – General Methods – for equipment details, pool calibration, video capture, video digitising, and data processing methods.

8.2.3 Data analysis and definition of variables

For definitions and calculation procedures for upper limb cycle phases, upper limb kinematics and body segment inclination angles, please refer to section 5.2.3. For definitions and calculation procedures for intra-cyclic speed fluctuation and Froude efficiency, please refer to section 7.2.3. Shoulder abduction angle (°) was obtained by projecting the elbow-shoulder and shoulder-hip vectors from the same side onto the XY plane and then calculating the angle between these projected vectors at the hand entry and hand exit. Shoulder abduction range of motion (°) was the difference between angles at hand entry and hand exit. All dependent variables are reported as the mean value obtained for each swimmer’s left and right limbs.

8.2.4 Statistical analysis

Means and standard deviations of all variables for the non-disabled swimmers were calculated. Individual data are presented for the three CMNI swimmers. To assess the relationship between stroke parameters, upper limb kinematics, intra-cyclic speed fluctuation and Froude efficiency in non-disabled swimmers, Pearson correlation coefficients were calculated. The threshold for statistical significance was set at $p < .05$

and defined as weak (< 0.3), moderate (0.3–0.6), or strong (> 0.6). To compare individual CMNI swimmer values with those of the non-disabled group, three-sigma limits was used to present the bounds within three standard deviations from the variable mean of the non-disabled group. If the CMNI swimmer's data fell outside this 99.7% confidence interval, a significant difference was deemed to exist between the CMNI swimmer and the non-disabled swimmers. All data were analysed using IBM SPSS Statistics 28.

8.3 RESULTS

8.3.1 Spatiotemporal variables (Table 8.2)

The swimming speed of the CMNI swimmers was approximately half that of the non-disabled swimmers, their stroke length was 32–42% shorter, and their stroke frequency was 26–44% higher. Of the CMNI swimmers, Swimmer A had the highest swimming speed and stroke length but the slowest stroke frequency, whereas Swimmer C had the lowest swimming speed and stroke length but the highest stroke frequency. The upper limbs of the CMNI and non-disabled swimmers spent ~31% of the cycle recovering over the water and ~69% of the cycle in the underwater phases. The relative time spent in pull phase was very similar across all three CMNI swimmers (~18%) but notably longer than in the non-disabled group (11 ± 2%). CMNI swimmers were more variable in the durations of their glide and push phases. Non-disabled swimmers pulled their hands on average 1.6 to 2.4 times deeper than the CMNI swimmers and their head-to-toe (y-axis) hand trajectory length, relative to the mass centre, was on average 30 to 40 cm longer than in the CMNI swimmers. Width of hand trajectory and hand trajectory slippage were similar between CMNI and non-disabled swimmers.

Table 8.2: Kinematic and spatiotemporal variables for non-disabled (n = 8) and three central motor and neuromuscular impaired swimmers in double-arm backstroke. [a] indicates where CMNI swimmer's score falls outside the 99.7% confidence interval of the non-disabled swimmers' mean score.

	CMNI swimmer (n=3)			Non-disabled swimmers (n=8)	99.7% confidence interval
	A	B	C		
Mean swimming speed ($m \cdot s^{-1}$)	0.56 [a]	0.50 [a]	0.49 [a]	1.07 ± 0.13	0.68 – 1.46
Stroke frequency ($stroke \cdot min^{-1}$)	40.5	44.8 [a]	46.2 [a]	32.1 ± 3.6	21.3 – 42.9
Stroke length (m)	0.83 [a]	0.67 [a]	0.63 [a]	2.00 ± 0.13	1.61 – 2.39
Glide phase (%)	21	8 [a]	1 [a]	19 ± 3	10 – 28
Pull phase (%)	18 [a]	18 [a]	17	11 ± 2	5 – 17
Push phase (%)	27 [a]	43	51 [a]	39 ± 3	30 – 48
Recovery phase (%)	34	31	31	31 ± 5	16 – 46
Hand trajectory depth (m)	0.16 [a]	0.19 [a]	0.24	0.39 ± 0.05	0.24 – 0.54
Hand trajectory width (m)	0.63	0.54	0.48	0.66 ± 0.06	0.48 – 84
Hand trajectory length (m)	1.10 [a]	1.00 [a]	1.11 [a]	1.42 ± 0.05	1.27 – 1.57
Hand trajectory slippage (m)	0.70	0.68	0.82	0.74 ± 0.09	0.47 – 1.01

Hand trajectories for a full upper limb cycle, as viewed along the x, y and z-axes, are presented in Figure 8.1. CMNI swimmers generally had less bi-lateral symmetry and shorter hand paths than the non-disabled swimmers. In contrast to the other swimmers, during the propulsive phases Swimmer A's hands remained in a horizontal plane. Swimmer B recovered his hands in a relatively low trajectory over the water compared to all other swimmers. Of the three CMNI swimmers, Swimmer C presented the closest vertical hand trajectory to those of non-disabled swimmers.

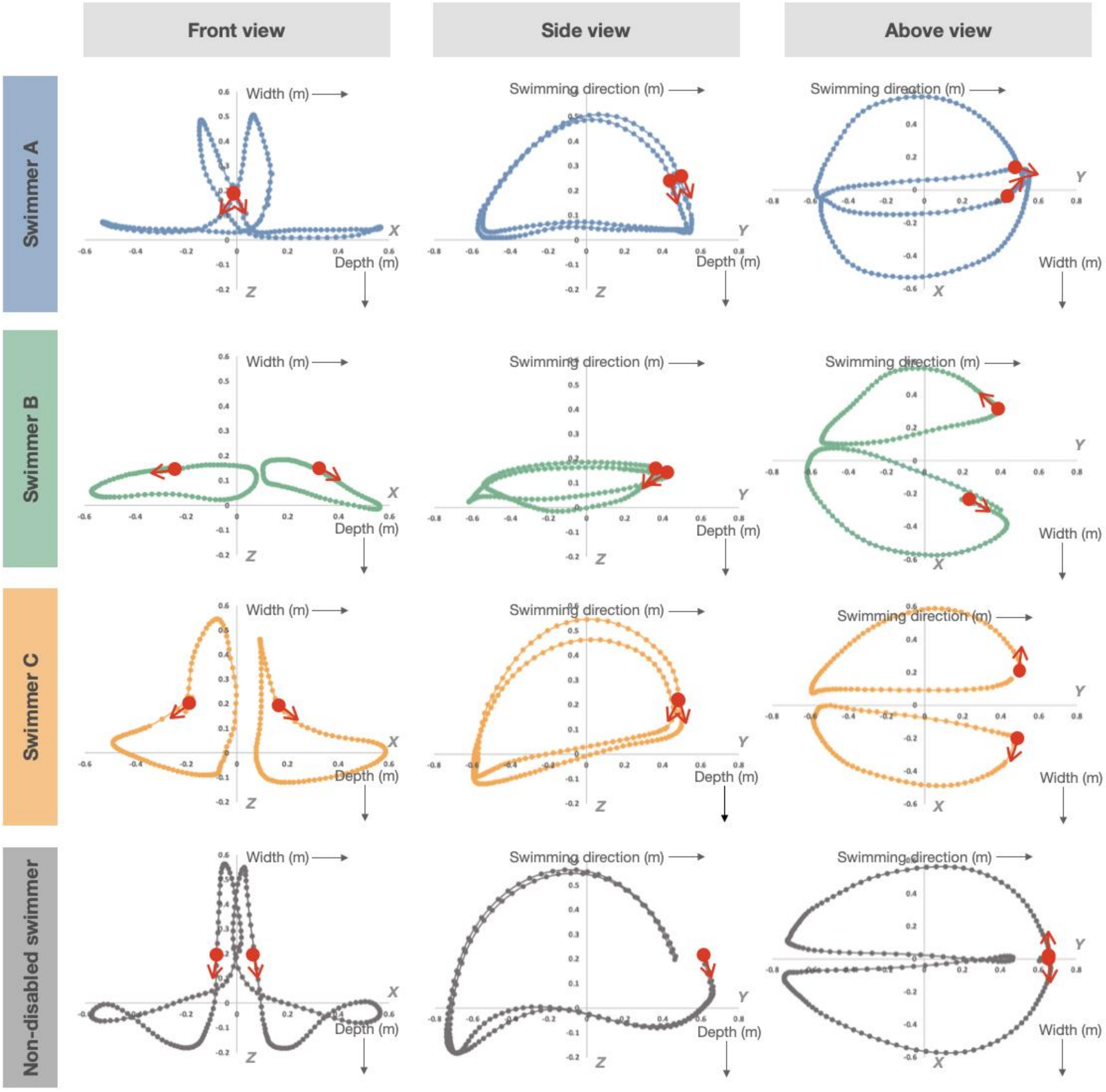


Figure 8.1: Left and right hand trajectories relative to a local coordinate system during a full upper limb cycle in double-arm backstroke. Views shown are front (y-axis), side (x-axis), and above (z-axis). Trajectories for the non-disabled group (n = 8) are mean curves. Individual trajectories are shown for the three central motor and neuromuscular impaired swimmers. The red arrow designates the start of the upper limb cycle (hand enters water) and the direction of travel.

8.3.2 Hand entry and exit (Figure 8.2)

Non-disabled swimmers’ hands entered the water 10 to 20 cm more superior to the head than CMNI swimmers’ hands did. Non-disabled swimmers tended to enter their hands into the water in line with the corresponding shoulder. In contrast, two of the CMNI swimmers entered 20–29 cm lateral of the shoulder, with the third entering 2 cm lateral to her shoulder on the left side and 8 cm medial to it on her right. Non-disabled swimmers' hands exited the water lateral to the hip. Conversely, the hands of the CMNI swimmers all left the water medial to the hip.

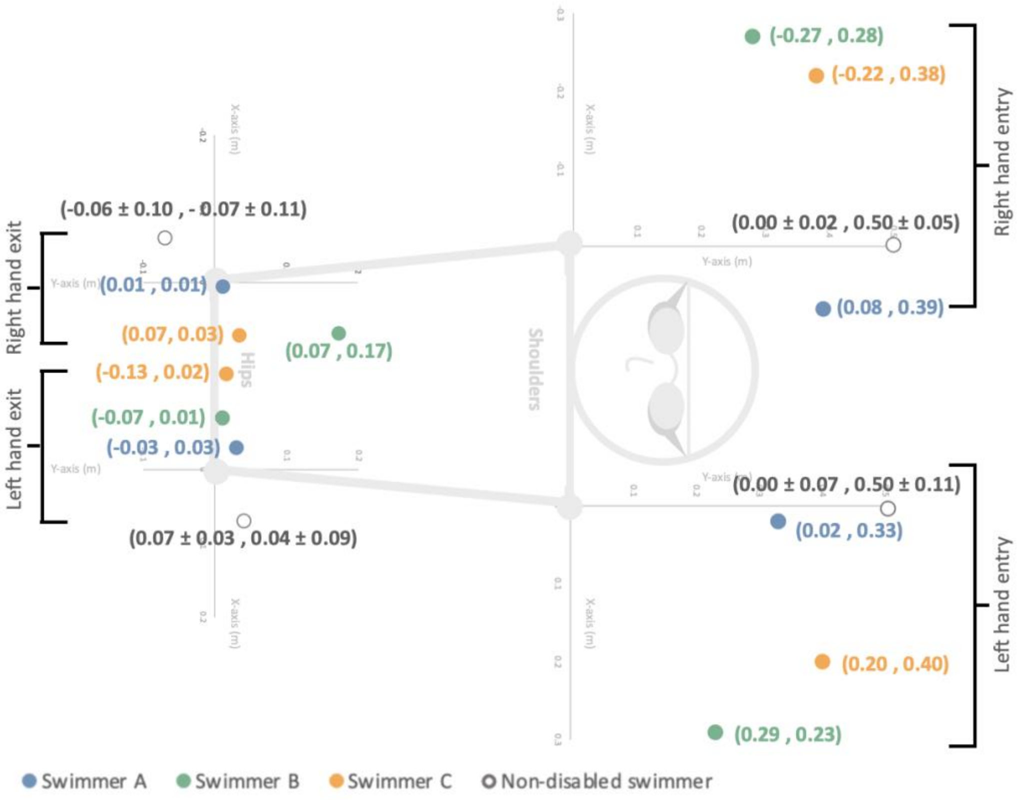


Figure 8.2: Location of hand entries (relative to same side shoulder) and hand exits (relative to same side hip) for non-disabled (n = 8) and three central motor and neuromuscular impaired swimmers performing double-arm backstroke.

8.3.3. Body segment inclination angles (Figure 8.3)

Compared to non-disabled swimmers, the CMNI swimmers presented greater trunk inclination, particularly Swimmers B and C, and their thighs were orientated past the horizontal (hips lower than knees). Shank inclination varied considerably between swimmers, with Swimmer C having the steepest shank orientation, more than double that of any other swimmer. Swimmer A had the most laterally aligned body position of all, with Swimmers B and C having the lowest hip and ankle positions. Body inclination angles (shoulder-to-knee) were similar across swimmers with and without impairment (Table 8.3).

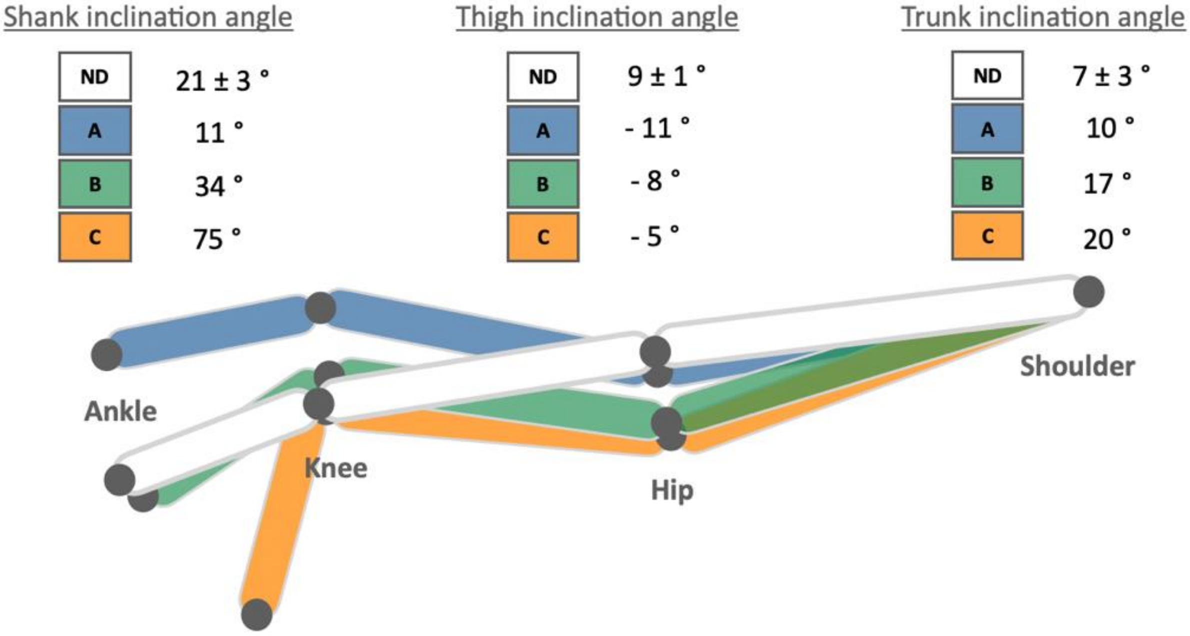


Figure 8.3: Body segment inclination angles during double-arm backstroke for non-disabled (n = 8) and three central motor and neuromuscular impaired swimmers. Images and values shown represent each segment's mean angle between hand entry and exit.

8.3.4. Hand configuration, hand position, hand speed and acceleration (Table 8.3, Figure 8.4)

There was no clear separation between the CMNI swimmers and the non-disabled group in any of the hand speed variables except the backward (y-axis) hand speed of Swimmer B, during his pull phase, which was less than half that of any other swimmer. Backward hand accelerations during the pull were all negative, denoting an increase in hand speed during this phase; conversely, backward hand accelerations were all positive during the push, indicating a slowing of hand speed in this phase. CMNI swimmer hand accelerations in the pull phase were similar to, or greater than, those observed in the non-disabled swimmers. In the push phase, the non-disabled group's mean hand acceleration was greater than those of the CMNI swimmers. During the underwater phases, the CMNI swimmers held different hand configurations to the non-disabled swimmers, as illustrated in Figure 8.4. Swimmers A and B had pronounced finger abduction and Swimmer C's hands were held in a loose fist; the non-disabled swimmers generally kept their fingers together. Compared to the non-disabled group, CMNI swimmers appeared to have less stability at the wrist as the hand was pulled through the water.

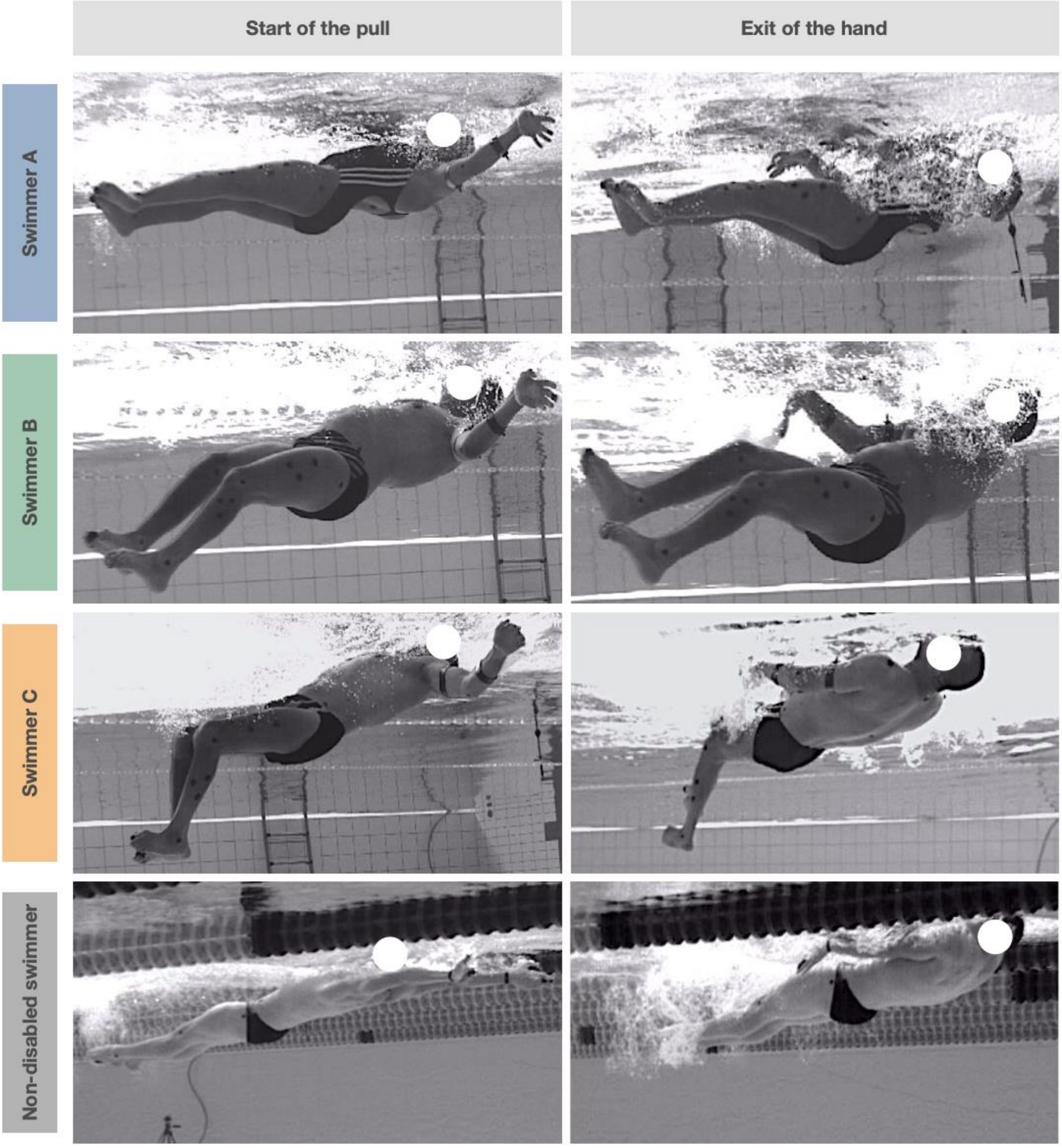


Figure 8.4: Body positions in double-arm backstroke at two instants: start of the pull (left) and exit of the hand (right) for three central motor and neuromuscular impaired swimmers and one non-disabled swimmer.

Table 8.3: Upper limbs kinematics, body inclination angle, intra-cyclic speed fluctuation and Froude efficiency in double-arm backstroke for non-disabled (n = 8) and three central motor and neuromuscular impaired swimmers. [a] indicates where CMNI swimmer's score falls outside the 99.7% confidence interval of the non-disabled swimmers' mean score.

	CMNI swimmer (n=3)			Non-disabled swimmers (n=8)	99.7% confidence interval
	A	B	C		
Mean hand speed x – pull ($m \cdot s^{-1}$)	1.09	0.90	1.38	1.02 ± 0.13	0.63 – 1.41
Mean hand speed x – push ($m \cdot s^{-1}$)	1.35	1.04	1.07	1.22 ± 0.29	0.35 – 2.09
Mean hand speed y – pull ($m \cdot s^{-1}$)	-1.39	-0.65 [a]	-1.47	-1.63 ± 0.30	-2.53 – -0.73
Mean hand speed y – push ($m \cdot s^{-1}$)	-1.07	-1.30	-1.43	-1.37 ± 0.25	-2.12 – -0.62
Mean hand acceleration y – pull ($m \cdot s^{-1}$)	-5.51	-10.80 [a]	-9.82	-6.07 ± 1.53	-10.66 – -1.48
Mean hand acceleration y – push ($m \cdot s^{-1}$)	7.24	4.16	6.36	8.80 ± 1.98	2.86 – 14.74
Elbow angle – start of pull (°)	139	131	154	143 ± 8	119 – 167
Elbow angle – start of push (°)	157	124	146	120 ± 13	81 – 159
Elbow angle – end of push (°)	147	136	130	147 ± 9	120 – 174
Elbow angle – hand exit (°)	137 [a]	138 [a]	142 [a]	169 ± 4	157 – 181
Elbow angle – re-entry (°)	136 [a]	127 [a]	161	168 ± 6	150 – 186
Elbow flexion during pull (°)	17	10	9	13 ± 8	-11 – 37
Elbow extension during push (°)	9	12	16	27 ± 11	-6 – 60
Elbow peak angular velocity during push ($rad \cdot s^{-1}$)	1.16 [a]	2.03 [a]	2.53 [a]	6.36 ± 1.26	2.58 – 10.14
Shoulder abduction at hand entry (°)	145	154	163	166 ± 7	145 – 187
Shoulder abduction at hand exit (°)	13	25 [a]	24 [a]	13 ± 3	4 – 22
Shoulder abduction range of motion (°)	132 [a]	129 [a]	139	153 ± 5	138 – 168
Body inclination angle (°)	2	8	9	8 ± 2	2 – 14
$ICSF_{\%}$ (%)	61	69	60	62 ± 12	26 – 98
$ICSF_{CV}$ (%)	19	18	20	20 ± 3	11 – 29
Froude efficiency	0.17 [a]	0.18 [a]	0.14 [a]	0.33 ± 0.02	0.27 – 0.39

8.3.5 Elbow and shoulder angle (Table 8.3)

CMNI swimmers started their push phase with 4–37° greater elbow flexion than the mean elbow flexion in non-disabled swimmers. Non-disabled swimmers had their elbows ~30° more extended than the CMNI swimmers at the instant of hand exit due to them performing 1.7 to 3 times more elbow extension during the push. The non-disabled swimmers' peak elbow extension angular velocity, during the push phase, was on average 2.5 to 5.5 times that of the CMNI swimmers. Regarding range of motion of the shoulder, CMNI swimmers had 3–21° less shoulder abduction at hand entry and 0–12° more abduction at hand exit, than non-disabled group. Swimmer B had the lowest range of shoulder abduction.

8.3.6 Intra-cyclic speed fluctuation and Froude efficiency

Although both $ICSF_{\%}$ and $ICSF_{\mathrm{CV}}$ in double-arm backstroke had similar values across all the participants, the shape of the swimming speed curves was not consistent within the CMNI swimmers, or between the CMNI and non-disabled swimmers (Figure 8.5). The non-disabled swimmers' speed generally peaked just before 50% of the cycle, which corresponded with the middle of the push phase, while the CMNI swimmers' speed curves had multiple peaks within the upper limb cycle. There were significant differences in Froude efficiency values between CMNI swimmers and non-disabled swimmers, with the value of the non-disabled swimmers was approximately double that of the CMNI swimmers.

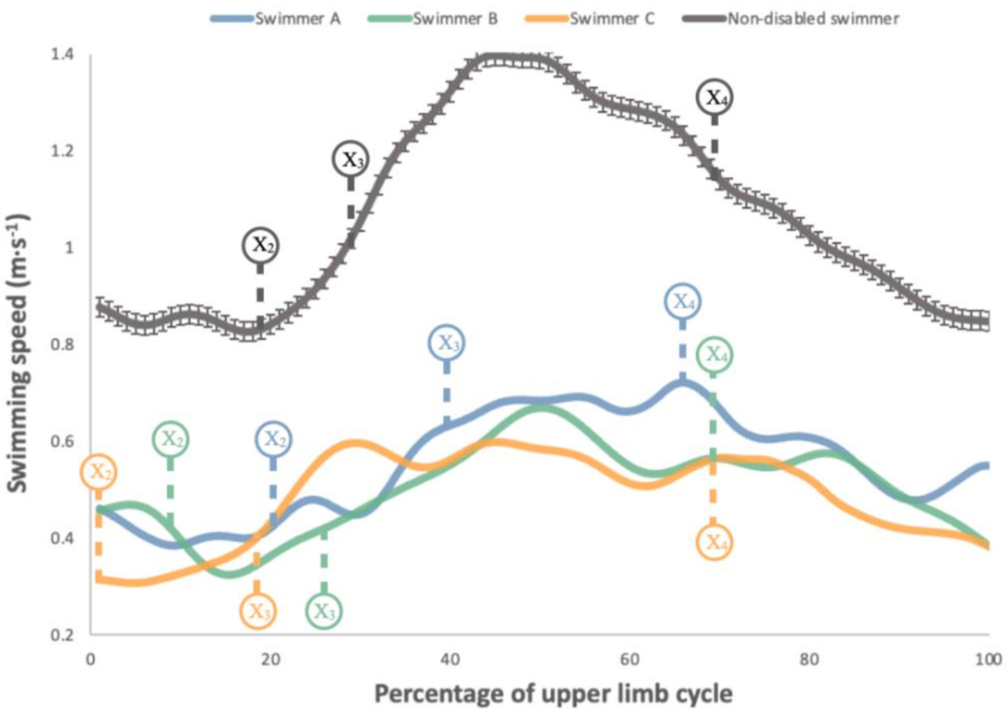


Figure 8.5: Swimming speed curves for a complete upper limb cycle for non-disabled (n = 8) and three central motor and neuromuscular impaired swimmers performing double-arm backstroke. Hand entry occurs at 0% of the cycle. Glide phase: 0%–X_1; Pull phase: X_2–X_3; Push phase: X_3–X_4; Recovery phase: X_4–100% (See section 5.2.3 for definitions of upper limb cycle phases).

8.3.7 Relationships between swimming speed, stroke frequency, stroke length and kinematic variables in non-disabled double-arm backstroke

A strong positive correlation was found between swimming speed and stroke frequency ($r = .86$, $p = .006$). $ICSF_{CV}$ had a strong negative correlation with swimming speed ($r = - .75$, $p = .033$). While $ICSF_{CV}$ was strongly correlated with $ICSF_{\%}$ ($r = .96$, $p < .001$), $ICSF_{\%}$ did not have an association with swimming speed nor with stroke length ($p > .05$). However, a strong negative correlation existed between $ICSF_{\%}$ and stroke frequency ($r = - .77$, $p = .026$). Although Froude efficiency did not correlate with swimming speed ($p > .05$), it had a strong positive relationship with stroke length ($r = .73$, $p = .040$).

8.4 DISCUSSION

The aim of this study was to quantify the impact of CMNI on performance determinants of double-arm backstroke. Non-disabled swimmers exhibited faster swimming speed, longer stroke length, but slower stroke frequency compared to CMNI swimmers. They also presented differences in upper limb kinematics, body segment inclination, and Froude efficiency. The first hypothesis was therefore accepted. Compared to front crawl technique, intra cyclic speed fluctuation in double-arm backstroke was greater in both non-disabled and CMNI groups. Froude efficiency, on the other hand, was significant lower in CMNI swimmers in double-arm backstroke compared to front crawl. This was not the case for non-disabled swimmers. The second hypothesis was therefore partially accepted. Different kinematic characteristics between the non-disabled and CMNI group can be explained by the effect of cerebral palsy. One of the key concerns in the population of cerebral palsy is the trunk instability (Bobath, 1991; Shin et al., 2017). The trunk is a fundamental element for motor control, losing this function may lead to abnormal body posture (Barnes and Johnson, 2001), poor head support by affected neck muscles (Hong, 2014), imbalance of the body (Ikai et al., 2003) and atypical upper and lower limb movements to help compensate the trunk instability (Hadders-Algra, 2005).

8.4.1 Upper limb kinematics

Non-disabled swimmers did not generally have faster hand speeds, relative to the water, than the CMNI swimmers during the pull and push phases. Although hand speed is an important determinant of propulsive force generation in the water (Kudo et al., 2012), there is no guarantee that a greater hand speed will lead to a higher swimming speed as a swimmer’s hand can slip through the water (Seifert et al., 2010c). Although the hand speed values relative to the water were comparable across the participants, the CMNI swimmers in the current study must have generated lower backward hand speeds, relative to their bodies, due to their slower swimming speed compared to non-disabled group. CMNI swimmers' hands slipped approximately 70% the length of their hand trajectory whereas it was only 50% for the non-disabled group. CMNI swimmers were unable to translate their hand speed into swimming speed, stroke length and Froude efficiency as effectively as non-disabled swimmers did.

Individuals with spastic cerebral palsy commonly exhibit upper limb deformities such as thumb-in-palm, swan neck or finger/wrist flexor deformity, or a combination of all (Choi et al., 2020). In non-disabled swimming, thumb position and finger spacing influence the propulsion a swimmer can generate from the hand (Marinho et al., 2010). Thus, it is likely that one factor contributing to the lower Froude efficiency of our CMNI swimmers is a compromised propelling surface as a result of their upper limb deformity. Moreover, Choi et al. (2020) pointed out that a dynamic wrist-finger flexor deformity was more detrimental to upper arm function than was a dynamic thumb-in-palm. Indeed, to swim forward effectively, a stabilised wrist is necessary to transmit the force from the hand to the body in the water (Caty et al., 2007). The poor wrist fixation and non-optimal finger positions observed in our CMNI swimmers would serve to reduce hydrodynamic forces on the hand and allow it to slip through the water more easily than a hand held with fingers together and controlled by a stable wrist. Thus, the hand speeds of the non-disabled group might have been moderated, in the pull and push phases, by higher hydrodynamic forces than those acting on the CMNI swimmers' hands, created by a more optimal propelling surface and stabilised wrist. One unanticipated result, given that hand acceleration is important for propulsion generation (Gourgoulis et al., 2015), was that the mean backward hand acceleration for the pull phase of the CMNI swimmers was similar to or greater than that of the non-disabled group. One explanation is that as non-disabled swimmers used considerably more vertical motion of the hand than the CMNI swimmers during the underwater phases, a larger component of their hand acceleration was directed in the vertical plane. Additionally, as described earlier, with the finger deformities and compromised wrist stabilisation, the CMNI swimmers' hands most likely experience less resistance from hydrodynamic forces and are thus more easily accelerated through the water.

The lower elbow and shoulder range of motion shown by the CMNI swimmers is likely related to impaired muscle strength (Hogarth et al., 2019a), shortened position of the muscles (Sindou et al., 2022), or a combination of both due to spasticity . Specifically, spasticity is often found in the shoulder external rotators, elbow, wrist and finger flexors, and the elbow pronators in the upper limbs (Klingels et al., 2012). It is apparent that our CMNI swimmers had difficulties pulling their hands deep in the water and fully extending their upper limbs at hand entry and exit. These limitations shorten the hand trajectory, relative to the body which reduces the potential stroke length. Swimmer B had the lowest elbow and shoulder range of motion, indicating he might have the greatest impairment at those joints. This caused his hand trajectory to be 11% shorter than Swimmer C. Despite his more restricted motion, he swam faster than Swimmer C, indicating that he may have less impaired muscle strength enabling more propulsion, generation, or lower drag. This highlights the need to establish the relative contribution that strength and active range of motion make towards propulsion generation in a CMNI population.

8.4.2 Body segment inclinations

Due to the supine body position in double-arm backstroke, without kicking the legs, swimmers probably need to actively lift their lumbar spine/hips from sinking down during the whole stroke cycle. In non-disabled backstroke, both greater hip depth and trunk inclination lead to a slower swimming speed (Stosic et al., 2021). This accords with our earlier observation which showed that CMNI swimmers had lower hip vertical position and greater magnitude of trunk inclination than non-disabled swimmers did in double-arm backstroke. This may be explained by their trunk instability (Shin et al., 2017), poor trunk control (Van der Linden et al., 2021) and unbalanced hip contractures (Yildiz and Demirkale, 2014) which hinder the ability to extend the trunk and raise the hips in the water. Moreover, CMNI swimmers used far less vertical hand motion underwater than the non-disabled swimmers so were not able to utilise these movements to lift their body during the push phase. Consequently, the relatively low body positions of the CMNI swimmers will inevitably result in higher drag coefficients, compared to the non-disabled group, due to the greater frontal area presented to the water (Kjendlie et al., 2004; Oh et al., 2013).

In addition to an inclined trunk, the poorly aligned thigh and shank segments of the CMNI swimmers will also contribute to drag generation. These abnormal postures could be related to the spasticity of the trunk muscles (Barnes and Johnson, 2001) where our CMNI swimmers did not have a stabilised trunk to achieve a horizontally aligned position as shown by the non-disabled swimmers. Within the CMNI group there is some evidence that the body segment inclinations influenced swimming speed. Swimmer C had the highest trunk and shank inclination with a swimming speed of 0.49 $m \cdot s^{-1}$ whereas Swimmer A had the least trunk and shank inclination with a swimming speed 0.56 $m \cdot s^{-1}$. Although no relationship existed between any single segment inclination angle and swimming speed, in non-disabled double-arm backstroke, some weighted combination of the segment angle may provide a useful metric to predict drag and swimming speed for CMNI swimmers.

It is interesting to note that although body inclination (shoulder–knee) is significantly related to swimming speed and stroke length in CMNI front crawl (see chapter 5), in double-arm backstroke this metric does not adequately reflect CMNI body position as CMNI swimmers' knees were either as high or even higher than those of non-disabled swimmers. Thus, body inclination did not differentiate between swimmers with and without an impairment in double-arm backstroke. It is necessary to consider a combination of the segment angles. The uniqueness of body orientations of our CMNI swimmers, dictated by their specific pathology, could be explained by the mechanisms of spasticity which re-establish a new connectivity of residual functions in partially impaired structures (Sindou et al., 2022). Therefore, even with the same impairment type, swimmers with CMNI demonstrated different body orientations in the water.

8.4.3 Intra-cyclic speed fluctuation and Froude efficiency

Compared to front crawl technique (See chapter 7) intra-cyclic speed fluctuation during double-arm backstroke was 3 to 5 times greater in non-disabled swimmers and 2 to 2.5 times greater in CMNI swimmers on average. This is due to the nature of a simultaneous upper limb movement and the absence of leg kick. $ICSF_{\%}$ and $ICSF_{CV}$ were significantly correlated with each other which supports the finding of (O'Dowd et al., 2023). Although the shape of the CMNI swimming speed curves were very different from non-disabled swimmers' curve, $ICSF_{\%}$ and $ICSF_{CV}$ did not differ between the groups. In Chapter 7 it was established that the calculations of $ICSF_{\%}$ and $ICSF_{CV}$ provide different insights. Specifically in double-arm backstroke, only $ICSF_{CV}$ was found to be associated with the swimming speed in non-disabled group. Perhaps $ICSF_{CV}$, which incorporates all the speed fluctuations during the cycle, is a more appropriate measure for this technique as $ICSF_{\%}$ only utilises a single maxima and minima from the cycle. Both $ICSF_{\%}$ and $ICSF_{CV}$ failed to distinguish between non-disabled and CMNI swimmers.

These metrics do not consider where in the cycle the speed fluctuations occurred.

Non-disabled swimmers were typified by a single speed peak whereas CMNI swimmers had multiple peaks in their speed curves. Changes in the speed curve indicate a mass centre acceleration caused by the resultant of the propulsive and drag force (Figueiredo et al., 2013b). An increase in speed denotes a net propulsive force; a decrease in speed signifies a net drag force. As non-disabled swimmers were able to hold a stable body position throughout the upper limb cycle, fluctuations in their speed curves will mainly reflect changes in their propulsion. Conversely, as the body segment angles of CMNI swimmers frequently changed in the cycle, the balance between propulsion and drag constantly shifted leading to multiple speed peaks. Moreover, the velocity-dependent hyperactive stretch reflex, also known as spasticity, could also explain the multiple small peaks occurred in CMNI speed curves as this impairment may increase tendon jerks, occasional clonus and other signs of upper motor neurone lesion (Levitt and Addison, 2018).

Froude efficiency is calculated from the swimmer's mass centre speed and their three-dimensional underwater hand speeds relative to their mass centre (Figueiredo et al., 2013b) and is lower in backstroke than in front crawl, at comparable swimming speeds (Gonjo et al., 2018). Our non-disabled swimmers demonstrated similar Froude efficiencies in their front crawl and double-arm backstroke, but their front crawl swimming speed was 85% higher than in their double-arm backstroke. As Froude efficiency increases with decreasing swimming speed (Gonjo et al., 2020), it is likely that if the non-disabled group performed front crawl at the same speed as their double-arm backstroke, Froude efficiency would have been far superior in the front crawl. On the other hand, CMNI double-arm backstroke swimmers in this study had 50% lower Froude efficiency compared to those CMNI swimmers able to perform front crawl (chapter 7). This could be attributed to their more severe impairment and the limitations inherent in the double-arm backstroke technique.

In the current study, the considerably higher Froude efficiency in the non-disabled group was due to them achieving a far superior swimming speed using similar three-dimensional hand speeds to the CMNI group. The relatively poor Froude efficiency in the CMNI group is likely linked to a combination of their impaired range of motion, affected muscle strength, the loss of trunk control, and short stroke length. Particularly, the hand entry location is an essential factor for CMNI swimmers as it establishes upper limb position at the start of the underwater phase. The relatively wide hand entry of Swimmers B and C may be associated with: (i) a reduced glide phase, as the hand moves almost directly into the pull phase, which is likely to reduce the opportunity to balance the body horizontally (Samson et al., 2015) and (ii) a shortened hand trajectory over which to create propulsion. In non-disabled double-arm backstroke, swimmers with longer stroke lengths presented greater Froude efficiency; this was not applicable in CMNI swimmers. Despite possessing the highest Froude efficiency, Swimmer B did not achieve the greatest stroke length. It is likely that his trunk and lower limb orientation were major influences limiting his stroke length and swimming speed. This is a common phenomenon observed across CMNI swimmers: their swimming speed was not only limited by reduced propulsion generation but also the amount of drag their abnormal postures would create. This observation was also made by Payton et al. (2020), but the current study adds further detail by providing Froude efficiencies and detailed information on CMNI body positions.

8.4.4 Limitations

This study could have benefited from having the three CMNI swimmers attempt a prone front crawl trial for comparison to their preferred freestyle technique in competition, double-arm backstroke. It was decided to not request this due to the swimmers' lack of experience in this technique and potential health and safety concerns. Only limited details of the CMNI swimmers' health condition were available. More information on their impairment would have aided our interpretation of some of the study results. The small sample size of CMNI swimmers (*n* = 3) precludes the use of inferential statistics and limits the generalisability of the results to the wider population. It should be noted that only a very small proportion of Para swimmers with CMNI worldwide compete using double-arm backstroke. For the non-disabled swimmers, double-arm backstroke was a relatively novel technique and they had limited time to practice it. It is likely that their performance variables, such as swimming speed, stroke length and Froude efficiency, would have been even higher following a greater learning period. Primarily for conciseness, left and right upper limb kinematics were presented as mean values. Although the double-arm backstroke is a relatively symmetrical technique, CMNI swimmers did demonstrate some bilateral asymmetry that has not been reported in this study.

8.5 CONCLUSION

This study presented the kinematic differences between non-disabled and CMNI swimmers performing double-arm backstroke. CMNI swimmers had approximately half the Froude efficiency of non-disabled swimmers which may be attributable to lower propulsion or higher drag due to their upper limb deformity, impaired active range of motion, affected muscle strength and abnormal body posture. CMNI swimmers were characterised by having more inclined trunk and lower limb segment orientations, reduced active range of motion at the shoulder and elbow, shallower hand trajectories and lower stroke length, compared to the non-disabled swimmers. Intra-cyclic speed fluctuation was similar between swimmers with and without an impairment. Double-arm backstroke had greater ICSF in both non-disabled and CMNI groups compared to front crawl technique. CMNI swimmers demonstrated a significant lower Froude efficiency in double-arm backstroke, whereas non-disabled swimmers presented a similar Froude efficiency as those in front crawl technique due to the difference in swimming speed.

As a case study, our swimmers with cerebral palsy had difficulties to extend their trunk and raise their hips in the water, demonstrating varied body orientations with different restraint in their upper limbs to generate propulsion. This study has highlighted the need for further research on CMNI swimmers to (i) establish the relationship between trunk muscle activation and swimming performance, (ii) confirm the impact of hand position and wrist control on propulsion generation and how these two factors interact, and (iii) establish the relationship between trunk and lower limb segment orientations, active drag and performance.

CHAPTER 9

EPILOGUE

This final chapter will recap the main findings of the thesis, highlighting the novel areas for each study; explain the substantial contribution the studies make to the current scientific body of knowledge; discuss the potential applications of the findings for those involved in Para swimming; outline the main limitations of the work and make recommendations for future work.

9.1 Recap of Findings

Study 1 has improved our understanding of the association between central motor and neuromuscular impairment (CMNI) severity and health conditions with freestyle stroke parameters. CMNI swimmers who swam with a bilateral kick exhibited shorter stroke length and slower swimming speed than non-disabled swimmers in both sprint and paced events. Importantly, stroke frequency was similar between healthy and impaired swimmers. Study 1 also examines the effect of CMNI severity on stroke parameters. As impairment severity (sport class) increased, stroke length and swimming speed decreased; stroke frequency did not differ across impairment severities in CMNI population. This is the first study to provide evidence that stroke length, rather than stroke frequency, was the limiting factor to CMNI freestyle performance. This warranted the more detailed analysis of CMNI freestyle kinematics (studies 2–5) using three-dimensional motion analysis to scrutinise and understand fully how CMNI limits stroke length and swimming speed.

Studies 2 and 3 compare the front crawl kinematics of non-disabled and CMNI swimmers. The former focusses on upper and lower limb, and trunk kinematics, the latter examines body roll kinematics. Study 2 has been one of the first attempts to thoroughly examine front crawl kinematics using 3D motion analysis in a group of CMNI swimmers. The findings suggested that these swimmers displayed lower swimming speed, stroke frequency and stroke length than non-disabled swimmers. This study is novel because it examined the body segment inclination angle and hand entry and exit positions in Para swimmers and illustrated how these differ from those of non-disabled swimmers. Study 3 is the first to present a detailed analysis of body roll kinematics in CMNI swimmers. Impaired swimmers exhibited less shoulder roll but greater hip roll than non-disabled swimmers. CMNI swimmers had atypical body roll profiles due to their reduced arm effectiveness and a weak or absent leg kick. This study is novel to illustrate a swimmer's body roll profile using angle-angle plot in front crawl swimming. Studies 2 and 3 also examine the relationship between CMNI and kinematic variables. Study 2 establishes that body and thigh inclination angles are indicators for impairment severity (sport class), swimming speed and stroke length. Stroke frequency, on the other hand, did not differ between impairment severities. Study 3 assesses the effect of CMNI on body roll by sub-grouping them into different levels of arm impairment (quantified by Froude efficiency) and leg impairment (defined by the number of legs a swimmer actively uses) derived from their performance. These are both novel approaches to categorising swimmers in Para swimming research.

Studies 2 and 3 examine how CMNI swimmers with a bilateral kick, unilateral kick or absent leg kick perform the front crawl stroke. As the effectiveness of their limb and trunk movements on whole body motion was not assessed, it was decided in study 4 to investigate Froude efficiency, Index of Coordination, and intra-cyclic speed fluctuation to gain further insight into the impact of CMNI on front crawl performance.

Study 4 provides the first comprehensive assessment of intra-cyclic speed fluctuation and Froude efficiency in a group of CMNI swimmers. These swimmers were found to have greater intra-cyclic speed fluctuation and lower Froude efficiency compared to a non-disabled group, reflecting a reduced ability to utilise fluid forces effectively during front crawl swimming. No difference existed in Index of Coordination between the groups. Study 4 also found that more severely impaired swimmers (lower sport class) had greater intra-cyclic speed fluctuation and lower Froude efficiency than less impaired swimmers. This study is the first to examine the effect of performance level on intra-cyclic speed fluctuation and Froude efficiency in CMNI swimmers.

Studies 2–4 focus on the biomechanical characteristics of those CMNI swimmers able to execute a version of front crawl, that is, they were prone and used alternating cyclic movements of their upper limbs. Given that not all of our CMNI swimmers were able to perform a front crawl technique, it was decided for the final study to investigate double-arm backstroke. Study 5 quantifies key kinematic variables in double-arm backstroke, a specialist freestyle technique, in three swimmers with severe CMNI and in a group of non-disabled swimmers. This study is the only empirical investigation into the impact of CMNI on double-arm backstroke. The non-disabled group had double the Froude efficiency of the CMNI group, whereas intra-cyclic speed fluctuation did not differ between the groups performing double-arm backstroke.

9.2 Contribution to body of knowledge

The new knowledge generated by this thesis can contribute to an improved, evidence-based classification system as it has identified some key determinants of freestyle performance in CMNI swimmers, an essential step in the process (Tweedy et al., 2016) (see section 1.5). Some of the key findings that could inform an improved classification system are: First, the examination of body segment inclination angles highlighted the abnormal body orientation in CMNI swimmers both in front crawl and in double-arm backstroke. These angles were highly predictive of CMNI freestyle performance and could be one of the criteria applied in the water-based assessment for this population. These angles could be obtained relatively quickly and accurately from 2D measures from a single camera. Second, the findings indicate that finger and wrist deformities in swimmers with cerebral palsy may affect their propulsion substantially compared to other impairment types. As such, hand position and wrist stability should be considered in their classification assessment. Third, intra-cyclic speed fluctuation and Froude efficiency both point toward a greater energy cost for CMNI swimmers performing freestyle. These two performance determinants could possibly be useful to classify CMNI swimmers, particularly in their longest distance event.

This thesis demonstrates indirectly that swimmers with CMNI experience impaired range of motion, affected muscle strength and poor coordination in the water which restrict their ability to perform freestyle in a comparable way to non-disabled swimmers. This reinforces the importance of having these three elements taken into account when classifying CMNI swimmers, rather than examining only one of them. Additionally, the ways in which CMNI limits swimming performance are different from those for swimmers with limb deficiency, leg length differences, or short stature. Therefore, it may be inequitable for these Para swimmers to compete together within the same class.

9.3 Limitations

While each study in this thesis had its specific limitations, a few more general limitations must be acknowledged: First, a high heterogeneity existed in the CMNI group. It was not feasible to recruit sub-groups of Para swimmers with the same or similar impairment severity, health condition and impairment location. As CMNI swimmers were combined to examine the freestyle kinematics, some effects of CMNI on freestyle performance cannot be separated between the CMNI severity, health condition and impairment location specifically. Second, the performance level of our CMNI group was not consistent; some had performed at national level, others were Paralympic champions. Third, the 3D data collection protocol sometimes permitted only one and a half upper limb cycle to be captured for analysis. It was assumed that the kinematic variables obtained from these cycles were typical of those used by the swimmer during the trial.

It must be acknowledged that some differences between the non-disabled and CMNI groups, unrelated to impairment, could have acted as confounding variables/covariates and thus have contributed to some of the difference found between the groups for certain kinematic variables. For example, the non-disabled group were on average 20 cm taller than the group with CMNI. This is likely to have contributed to the greater stroke length and hand trajectory depth observed in the non-disabled group. Similarly, the sex of the participant is likely to have influenced some of the dependent variables. There were insufficient numbers in the CMNI and non-disabled groups to conduct any meaningful analyses for the separate sexes, so the sexes were pooled.

The majority of participants in both groups were male and this was proportionally higher in the non-disabled group introducing a gender bias within and between groups that must be acknowledged. How this influenced the results is difficult to determine as, for example, one of the female non-disabled swimmers was taller than all but one of the entire study cohort, had the greatest body mass and achieved stroke lengths that were comparable to the mean for the non-disabled males. There is little evidence to indicate that sex has a significant effect on the key variables in studies 3 (body roll kinematics) and 4 (Froude Efficiency, Index of Coordination and intra-cyclic speed fluctuation). However, it is recognized that kinematic differences between sexes do exist in other sports movements, for example in a soccer kick female athletes exhibit greater hip extension/flexion than males (Shan et al., 2005; Smith and Gilleard, 2016).Other potential confounding variables that could have influenced the swimmers' kinematics include their performance level, training and health status, and level of technical coaching received. Although all participants were designated as highly-trained, it is inevitable that some differences would exist in these variables.

This thesis could have benefited from having a more detailed health condition of our CMNI swimmers to support the interpretation of some of the experimental data. For instance, knowledge of the participants' spinal cord injury level would clarify which limbs are likely affected and which should be unimpaired by the injury; knowledge of the participants' type of cerebral palsy (spastic, hypotonic, athetoid, ataxic, and combination) would help understand the nature of their movement impairment and how this might constrain their movements when they are swimming.

Finally, although the current classification system is criticised as being subjective and flawed, it is current best practice (Tweedy and Vanlandewijck, 2011). The sport class is imperfect, however, this thesis discovered that sport class was generally correlated well with swimming performance and its determinants, i.e., swimming speed, stroke length, body/thigh inclination angles, intra-cyclic speed fluctuation and Froude efficiency. This provides some evidence supporting that the current sport class does reflect swimming-specific impairment severity to some extent.

9.4 Future Research Directions

This thesis highlights a number of areas for future research that would advance our understanding of the link between swimming performance and CMNI and thus contribute to the development of an improved evidence-based classification system in Para swimming. This thesis provides detailed kinematics of highly trained CMNI swimmers specifically in freestyle performance. Due to the technical differences between the competitive strokes (front crawl, backstroke, breaststroke, butterfly) and the demands of different race distances (50 m–400 m), the relative contribution of the upper and lower limbs to propulsion will change according to the stroke performed and distance raced (Hogarth et al., 2018). Future research needs to adopt a stroke/event-specific approach to establish the key performance determinants for

CMNI swimmers. Our participants performed unfatigued at their 100–200 m race pace and were instructed to hold their breath while swimming through the calibrated volume. The effect of fatigue and breathing action on CMNI freestyle performance thus remain unclear and warrant investigation.

A detailed analysis of CMNI shoulder motion was not conducted within the current thesis, although the findings suggested that more restricted shoulder motion may impede the amount of propulsion their upper limbs generate. An analysis of the glenohumeral joint motion, including flexion-extension, horizontal flexion-extension, and internal-external rotation, is needed to determine whether abnormal shoulder motion exists in CMNI population. In addition, cerebral palsy can affect hand position and wrist control, therefore, disadvantaging these swimmers in terms of propulsion generation. Future research, possibly through the use of computational fluid dynamics, should address the impact of hand position and wrist control on propulsion generation in CMNI swimmers.

This thesis shows that thigh/body inclinations can distinguish impairment severity in CMNI swimmers and serve as an indirect measure of drag coefficients in front crawl. Further research to establish the precise relationship between thigh/body inclinations and passive and active drag in CMNI swimmers is strongly recommended. The atypical body roll and abnormal body orientation in CMNI swimmers reported in this thesis provided some evidence of the poor trunk muscle control in this population. These findings raise several important questions including: (i) how does the trunk muscle activation correlate with CMNI type and severity? (ii) how does trunk muscle activation influence CMNI front crawl performance? Future work could explore these areas using electromyography to assess trunk muscle activity in CMNI swimmers.

Finally, the findings of this thesis could inform the development of a classification measurement tool that provides a global 'technique profile score' for CMNI swimmers in the water test. The kinematics of the upper and lower limbs and trunk could be scored on a ratio scale, according to their effectiveness in generating propulsion or reducing drag, and then benchmarked against a non-disabled group, with a higher technique profile score representing a more comparable movement pattern to non-disabled swimmers. This water-based technique profile could then be used to validate the existing land-based measurements of impairment currently used in classification and inform the development of new tests such as the tapping test for motor coordination (Hogarth et al., 2019b), the trunk impairment test (Smith et al., 2021), the upper and lower limbs isometric strength test (Hogarth et al., 2019a), and the active range of motion test (Nicholson et al., 2018).

9.5 Conclusion

It is challenging to gain insights into the impact of CMNI on freestyle performance due to each CMNI swimmer being quite unique in their impairment severity, health condition and impairment location. This thesis highlights indirectly the impact of impaired active range of motion, affected strength, and poor coordination on CMNI freestyle kinematics. In addition, it reveals that CMNI swimmers are characterised by having irregular hand and wrist positions, shallow and short hand trajectories, restricted elbow and shoulder active range of motion, atypical body roll profiles, affected function of upper and lower limbs, and more inclined body orientations, in freestyle, compared to non-disabled swimmers. Finally, CMNI swimmers' reduced ability to generate propulsion, minimise drag and swim economically is evidenced, indirectly, by the findings of lower Froude efficiency and greater intra-cyclic speed fluctuation than non-disabled swimmers. The thesis has improved our understanding of the biomechanical determinants in CMNI freestyle swimming and, in doing so, may contribute to the future improvement of the Para swimming classification system.

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Appendices

Appendix 1

Publication

D1.S3.3(5) Front crawl body roll characteristics of highly trained swimmers with central motor and neuromuscular impairments

YU-HSIEN LEE[1], DAWN O'DOWD[1], LUKE HOGARTH[2], BRENDAN BURKETT[2] AND CARL PAYTON[1]

[1]Manchester Metropolitan University, UK; [2]University of the Sunshine Coast, Australia

Rotation of the body about its long axis, commonly referred to as body roll, is an essential feature of front crawl swimming. Body roll may facilitate the breathing action, aid over-water recovery of the arm, increase propulsion, decrease drag, and reduce shoulder injury risk. Body roll involves rotation of the entire trunk combined with a twist of the trunk such that the hips and shoulders may achieve different amplitudes, possibly at different times in the stroke cycle (Yanai, 2001, Journal of Applied Biomechanics, 17, 28–42). Swimmers with central motor and neuromuscular impairments (CMNI), such as cerebral palsy, typically find it challenging to perform the rhythmic and coordinated movements required in front crawl. It is hypothesised that front crawl swimmers with CMNI will present atypical body roll characteristics. This study aims to: (i) compare body roll kinematics between non-disabled swimmers and those with CMNI and (ii) examine the effect of impairment severity (sport class) on body roll. With approval from the Manchester Metropolitan University Ethics Committee, 27 Para swimmers (S1–S9) with an eligible CMNI were recorded by six synchronised cameras while performing front crawl. 3D shoulder and hip coordinates were obtained for a full stroke cycle at 50 Hz. Shoulder and hip roll angles were defined by projecting the vectors linking each joint pair onto the plane perpendicular to the swimming direction. CMNI swimmers' shoulder roll range (88 ± 21°) was well below values (107 ± 8°) reported for skilled non-disabled swimmers (Psycharakis and Sanders, 2008, Medicine & Science in Sports & Exercise, 40, 2129–2136), whilst their mean hip roll range (75 ± 29°) was notably greater than values reported (50 ± 12°) for the same non-disabled group. Shoulder and hip roll asymmetries were higher in CMNI swim- mers (10 ± 7° and 10 ± 8°, respectively) than in the non-disabled group (8 ± 5° and 6 ± 4°, respectively). No association was found between impairment severity (sport class) and any body roll metric. CMNI swimmers with a strong leg kick exhibited greater hip roll range (88 ± 37°) and mean hip roll angular speed (129 ± 31°·s^{-1}) than those with a weak or absent leg kick (74 ± 29° and 96 ± 38°·s^{-1}, respectively). CMNI swimmers displayed differences in shoulder and hip roll range and asymmetries, compared to non-disabled swimmers. These differences may hinder their ability to generate propulsion and minimise drag, and consequently limit swimming speed.

Appendix 2

Participants Information Sheet and Consent Form

MANCHESTER METROPOLITAN UNIVERSITY

Department of Sport and Exercise Sciences

Information Sheet for Participants

Title of Study: Classification of Para swimmers with physical impairments

Ethics Committee Reference Number: 100517-ESS

Participant Information Sheet

1) This is an invitation to take part in a piece of research.

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Please take time to decide whether or not you wish to take part.

2) What is the purpose of the research?

The purpose of the study is to assess some important technical factors which affect freestyle swimming performance, e.g. co-ordination, propelling efficiency, body roll, speed fluctuation. The study will provide World Para Swimming with clear recommendations on what should be measured during the classification process. For this research, we need to assess high level Para swimmers and swimmers who do not have any physical impairment. The latter will act as a 'control group'.

3) Why is the study being performed?

World Para Swimming has decided that the current Para swimming classification system needs to be updated. UK Sport and World Para Sport are jointly funding this research project that will provide a scientific evidence base from which a revised or new Para swimming classification system can be developed.

4) Why am I being asked to take part?

As a highly trained swimmer without any physical impairment your participation in this project will provide us with vital performance data that that we can compare to data from elite Para swimmers. This will lead to an improved system for classifying Para swimmers in the future.

5) Do I have to take part?

You are under no obligation to take part in this study. If, after reading this information sheet and asking any additional questions, you do not feel comfortable taking part in the study you do not have to. If you do decide to take part you are free to withdraw from the study at any point, without having to give a reason. If you do withdraw from the study you are free to take any personal data with you, on written request to the Principal Investigator, and this will not be included when the research is reported. If you decide not to take part or withdraw from the study, this will not affect your relationship with any of the staff at the Manchester Metropolitan University.

If you do decide to take part you will be asked to sign an informed consent form stating your agreement to take part. You will be given a copy of the consent form together with this information sheet to keep. If you are under the age of 18, we will be asking for your agreement to participate and also the consent of your parent(s) or guardian/carer.

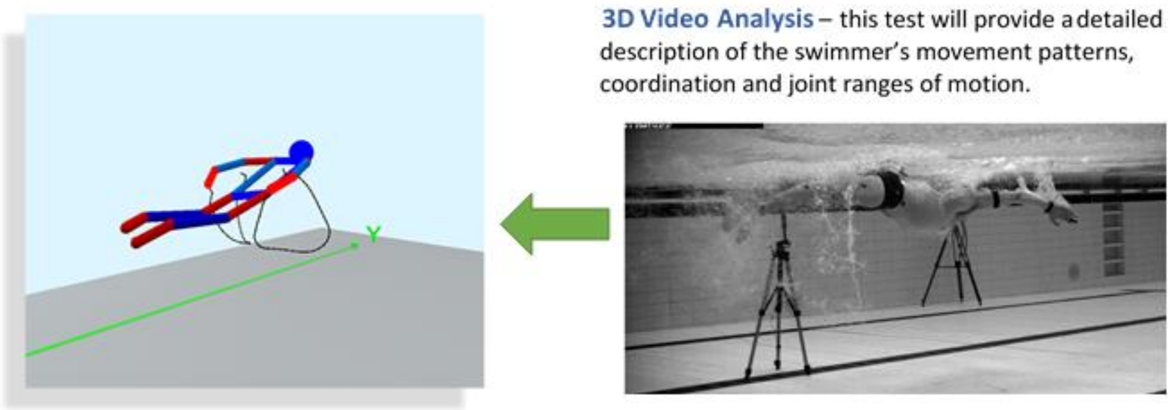
6) What will happen to me if I agree to take part?

If you agree to participate, you will be asked to complete the test described below. The test will be conducted in a single session

Description of Test

3D video test (~30 mins) – this test will involve you swimming 3-4 25 m trials from a push start while being recorded from multiple video cameras above and below water. Prior to the swims, we will place black markers (dots and bands) on each of your limbs, at specific sites, e.g. ankle, knee, hip to aid our analysis. These markers will be achieved using waterproof marker pen and black tape.

1 x 25 m Freestyle @ 200 pace
1 x 25 m Freestyle @ 50 pace
1 x 25 m double-arm backstroke (arms-only)
+ trial(s) of athlete's / coach's choice as required



3D Video Analysis – this test will provide a detailed description of the swimmer's movement patterns, coordination and joint ranges of motion.

7) Are there any disadvantages or risks in taking part?

The risks of taking part are minimal. All videos will be anonymized after data collection, but you may still be recognizable through swimming costume, body markings or tattoos.

8) What are the possible benefits of taking part?

Following your participation, you will be provided with an individual report that summarises your test results and high quality underwater video footage of your swimming. This report and the video footage may be of benefit to you and your coach in planning your training.

9) Who are the members of the research team?

The team comprises Prof. Carl Payton (Principal Investigator), Dr. Dawn O'Dowd, Victoria Jones and Lexie Lee. We will be responsible for running the tests described in Section 6, analysing the data collected and providing you with feedback on your results. If you would like further information on the project, the Principal Investigator.

Principal Investigator: Prof. Carl Payton: C.Payton@mmu.ac.uk 0161 247 5451

10) Who is funding the research?

The project is jointly funded by World Para Sport, UK Sport and Manchester Metropolitan University.

11) Who will have access to the data?

Only the Principal Investigator and the research team members will have access to the video recordings. World Para Swimming may be given access to the processed data arising from the analysis, but these will be anonymized or coded at the point of data collection. All data will be stored on a secure PC with a password. A back-up copy will be stored on an external password protected hard-drive.

Photographs and video recordings will retained for the duration of the project (24 months) and then destroyed (files deleted). However, prior to this, your video recordings will be made available to you and your coach (with your written consent).

The results of the study are likely to be communicated at conferences or published in scientific journals at some point in the future but in a manner that does not allow an individual's identity to be determined. You have the right to obtain a copy of any publication that results from the research. To do this you should contact the Principal Investigator.

12) Who do I contact if I feel my rights have been violated?

If you wish to make a complaint regarding your involvement in the study, please contact:

MMU Ethics Committee
Registrar & Clerk to the Board of Governors
Head of Governance and Secretariat Team
Manchester Metropolitan University
All Saints Building, All Saints
Manchester M15 6BH
Tel: 0161 247 1390

I confirm that the insurance policies in place at Manchester Metropolitan University will cover claims for negligence arising from the conduct of the University's normal business, which includes research carried out by staff and by undergraduate and postgraduate students as part of their course. This does not extend to clinical negligence.

13) Finally, a thank you!

Thank you very much for considering participating in this study.

EthOS ID: 100517-ESS

Participant Identification Number:

CONSENT FORM

Title of Project: Classification of Para swimmers with physical impairments

Name of Researcher: Prof. Carl Payton (DoS), Lexie Lee (PhD Candidate)

Please initial box

1. I confirm that I have read the information sheet dated 05/01/2023 (version 1.0) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal rights being affected. ☐
3. (If appropriate) I understand that relevant sections of the data collected during the study, may be looked at by individuals from Manchester Metropolitan University and others collaborating on this project. I give permission for these individuals to have access to my records. ☐
4. (If appropriate) I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other researchers. ☐
5. I agree to take part in the above study. ☐

Name of Participant Date Signature

Name of Person taking consent Date Signature

Version: 1.0. Date: 05/01/2023 **Page 1/1**
Ethical approval number (EthOs): 100517