Movement Characteristics of Front Crawl Swimming at Sprint Pace and Middle-Distance Pace:
Establishing Demands on the Torso Muscles

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Abstract

Dry-land strength for the torso muscles is a common component of swimming programs. The physical requirements of the torso muscles during front crawl swimming, however, is unclear. The purpose of this thesis was to establish the demands on the torso muscles during front crawl swimming from analysis of rotation about the body's longitudinal axis and torso muscle activity data during sprint and middle-distance front crawl. Three studies were conducted to examine movement patterns in front crawl swimming.

In the first two studies, three-dimensional (3D) kinematic data from national and international Scottish front crawl specialists were analysed. Participants swam front crawl for 4x25m trials at sprint pace and a 400m trial at a pace equal to their 400m race pace in a randomised order. Swimmers' motion was captured by six synchronised cameras (2 above and 4 underwater).

Thirteen swimmers were included for analysis in Study 1. Torso twist, determined as the relative angle between shoulder and hip roll, and the time derivatives (i.e. velocities) of hip roll, shoulder roll, and torso twist were calculated at sprint and 400m pace. Hip roll range decreased as swimming speed increased, despite an increase in stroke frequency, while shoulder roll range was similar between paces. These differences between paces produced a greater range (sprint: 78.1^{o}; 400m: 61.3^{o}) and velocity of torso twist (sprint: $166.3^{o}/s$; 400m: $96.9^{o}/s$) as swimming speed increased, indicating that the torques that produce rotation between the upper and lower torso may be greater at sprint pace than at 400m pace.

In Study 2, angular momenta of fourteen swimmers were calculated from 3D coordinate and anthropometric data to determine the impact of the flutter kick on body rotation about the longitudinal axis. Fourier analysis was used to decompose angular momentum signals into the first three harmonic frequencies. The third harmonic frequency (H3) was used to represent the effects of rotation from the flutter kick. H3 amplitude was significantly greater in lower limb than in upper limb angular momentum at both paces, indicating a “filtering” effect of rotation from the flutter kick when it is transferred from the lower limbs to the upper limbs. The “filtering” effect was more pronounced at sprint pace than at 400m pace.

In Study 3, 3D kinematic and torso muscle electromyography (EMG) data were collected from fifteen competitive Portuguese swimmers. Participants swam 4x25m trials at 400m pace and 4x25m trials at sprint pace. Muscle activity from internal oblique, external oblique, rectus abdominis, lumbar erector spinae, and thoracic erector spinae were measured using surface EMG. Participants’ motion was captured using Qualisys. Torso twist was the relative angle between thorax and pelvis rotation about the longitudinal axis and torso twist acceleration was calculated. Integrated EMG (iEMG) was calculated over one complete cycle of thorax rotation. Full-wave rectified EMG data were also integrated over 10ms intervals and normalised to the maximum value during each cycle (%iEMG). Average %iEMG and torso twist acceleration was calculated for each 5th percentile of the cycle. Spearman Rank-Order correlation tests were used to evaluate the relationship between muscle activity and torso twist acceleration for individual trials. iEMG scores of internal oblique, external oblique, and rectus abdominis were greater at sprint pace than at 400m pace but lumbar and thoracic erector spinae iEMG were similar between paces. Differences in thorax and pelvis angles created an interference pattern, producing a wide range of sinusoidal patterns in torso twist angle. Changes in torso twist angle did not appear to relate to torso muscle EMG data and no relationships between torso muscle activity and torso twist acceleration could be detected. The findings from this study indicated that the torso muscles may play a greater role in stability and posture in front crawl than they do in producing torso twist.

The findings from this thesis produced insights into the demands on the torso muscles in front crawl and the following guidelines were developed to improve the specificity of dry-land training for swimmers:

1. When preparing a swimmer for a specific event distance, increase the demands on the torso muscles as swimming speed increases.
2. Use the torso muscles to provide stability during lower limbs movements.
3. Challenge the torso muscles to maintain torso posture while moving the upper and lower limbs.

Acknowledgments

I would like to extend my gratitude to my supervisors, Dr Ross Sanders and Dr Peter Sinclair. You challenged me throughout my degree and for that I am extremely thankful. I have met some amazing people with whom I have no doubt I will share life-long friendships with because of your long-standing relationships with some of the best researchers in the world. Thank you for asking me to do better and for never settling for “good enough”.

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Publications and Presentations

Published Journal Articles

A portion of the review of literature in Chapter 2 was published as:

> **Andersen J** & Sanders R (2018). A systematic review of propulsion from the flutter kick – What can we learn from the dolphin kick? *Journal of Sports Sciences, 36*(18), 2068-2075.

The study in Chapter 3 was accepted for publication as of 30th May 2019:

> **Andersen J**, Sinclair P, McCabe C, Sanders R (2019, ahead of print). Kinematic differences in shoulder roll and hip roll at different front crawl speeds. *Journal of Strength & Conditioning Research*.

Published Conference Papers

The study in Chapter 4 was orally presented at the 36th International Conference on Biomechanics in Sports in Auckland, New Zealand, 10-14 September 2018 (Appendix G). The proceedings from this congress are published annually as four-page conference papers:

> **Andersen J**, Sinclair P, McCabe C, Sanders R (2018). The application of Fourier analysis to demonstrate the impact of the flutter kick on longitudinal rotation in front crawl. *ISBS Proceedings Archive, 36*(1), Article 223. Available at: https://commons.nmu.edu/isbs/vol36/iss1/223.

A portion of Chapter 5 was orally presented at the 37th International Conference on Biomechanics in Sports 2019 to be held in Oxford, Ohio, USA 22-26 July 2019 (Appendix

H). The proceedings from this congress are published annually as four-page conference papers:

> **Andersen, J T**.; Sinclair, P; Fernandes, R; Vilas-Boas, J P; and Sanders, R (2019) Do the torso muscles produce torso twist in front crawl?, *ISBS Proceedings Archive*: Vol. 37: Iss. 1, Article 83. Available at: https://commons.nmu.edu/isbs/vol37/iss1/83.

Conference Presentations

Findings from Chapter 3 were included in an oral presentation at the XIIIth International Symposium on Biomechanics and Medicine in Swimming held in Tsukuba, Japan 17-21 September 2018:

> **Andersen J**, Sinclair P, McCabe C, Sanders R (2018). Differences in rotational kinematics about the longitudinal axis in front crawl swimming from three-dimensional digitised video: Implications for torso muscle training. *Abstract Presentation at the XIIIth International Symposium on Biomechanics and Medicine in Swimming*. 17-21 September 2018, Tsukuba, Japan.

Published Book Chapter

In addition to the works that comprise this thesis, contributions were made to a book chapter that was not included in this thesis. The book chapter was published as:

> Sanders R.H., **Andersen J.T**., Takagi H. (2017). The Segmental Movements in Front Crawl Swimming. In: Müller B. et al. (eds) Handbook of Human Motion. Springer, Cham.

Authorship Attribution Statement

I, **Jordan Andersen**, certify that the studies in this thesis that were published and/or presented at scientific conferences were designed by me. In addition, I analysed the data and was the principal and corresponding author for the works listed above, with the exception of cases where I am not listed as the first author for a published item.

Signature

Name Jordan Andersen

Date 27th of March 2019

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Signature:

Date: 27-03-2019

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Physical Activity, Lifestyle, Ageing and Wellness,

Faculty of Health Sciences,

The University of Sydney.

Statement of Originality

I, **Jordan Andersen**, certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

This is to certify that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

In addition, ethical approval from the University of Edinburgh, Scotland Human Ethics Committee was granted for the studies in Chapters 3 and 4 presented in this thesis. Ethical approval from the University of Porto, Portugal Human Ethics Committee was granted for the study in Chapter 5 presented in this thesis. Participants were required to read a participant information document and informed consent was gained prior to data collection. For participants under the age of 18, participants and a parent or guardian provided written consent.

Signature

Name Jordan Andersen

Date 27th of March 2019

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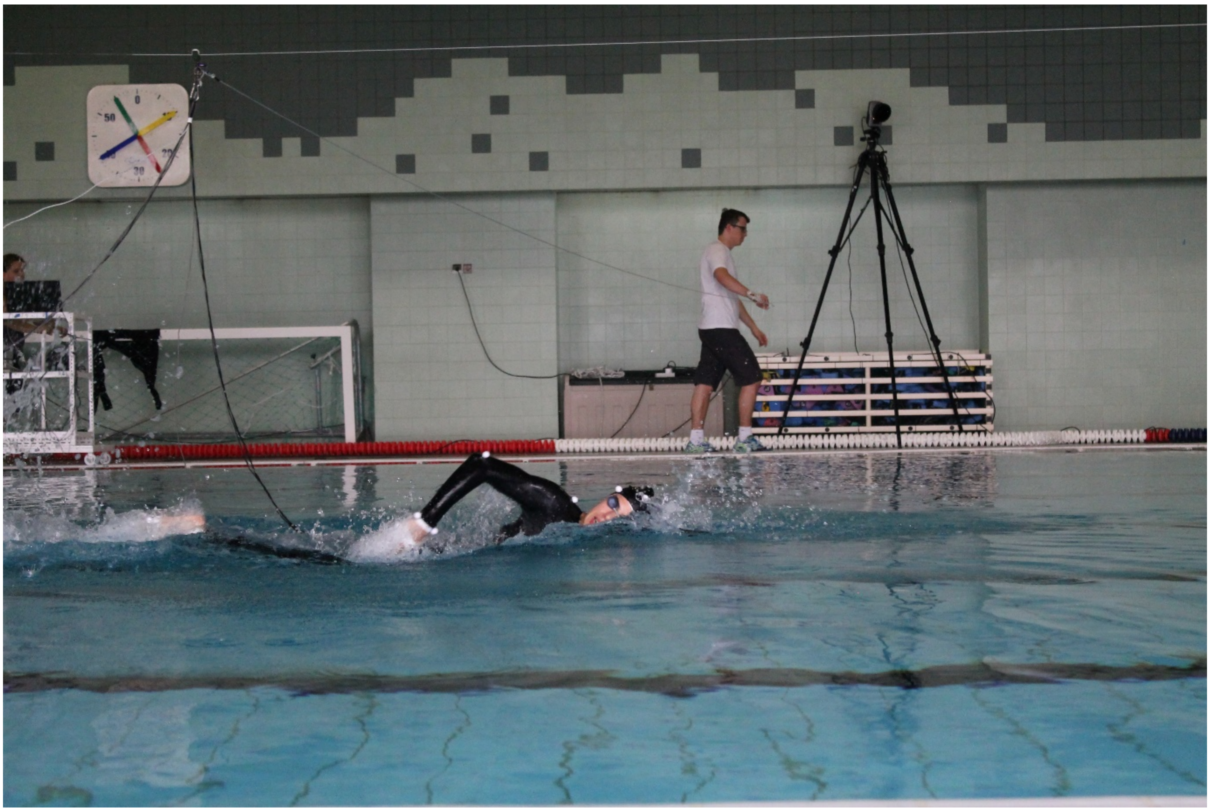
CHAPTER 1:

Introduction



Although the efficacy of dry-land strength training in swimming is contentious (Aspenes & Karlsen, 2012), it is a common component of swimming programs. Dry-land exercises are often designed to condition the torso muscles and swimmers frequently include twisting movements with their torso. For example, a typical exercise requires swimmers to produce axial rotation about the spine and throw a medicine ball to one side using a twisting movement of the torso. These exercises may be included in dry-land strength training because of the importance of body rotation about the longitudinal axis for swimming performance (Psycharakis & Sanders, 2010). It is unclear, however, whether swimmers use their torso muscles to generate rotation between the upper torso (e.g. the thorax) and lower torso (e.g. the lumbosacral spine and the pelvis) in front crawl. Though torso muscle training has been associated with improvements in front crawl performance (Weston, Hibbs, Thompson, & Spears, 2015), there is a paucity of evidence for determining how dry-land exercises for the torso muscles should be designed to maximise training specificity for front crawl swimming.

Strength training must be based on the demands of a sport to maximise the probability that training adaptations transfer to improvements in performance (González-Badillo & Sánchez-Medina, 2010; Izquierdo, Häkkinen, Gonzalez-Badillo, Ibanez, & Gorostiaga, 2002). By examining movement characteristics in front crawl swimming, the demands of front crawl swimming (i.e. the actions of the torso muscles required to produce front crawl movements) can be understood and guidelines developed for dry-land strength training for swimmers. Knowledge of body rotation about the longitudinal axis and torso muscle activity patterns during front crawl swimming can be used to guide the design of land-based exercises and improve training specificity.

The rotations of the shoulders and hips about the body’s longitudinal axis in front crawl swimming, known respectively as shoulder roll and hip roll, follow a sinusoidal rhythm

(Psycharakis & Sanders, 2010; Yanai, 2003). Though the rhythms of hip roll and shoulder roll are similar in front crawl (Sanders & Psycharakis, 2009), there are differences between the range of shoulder roll and the range of hip roll (McCabe, Psycharakis, & Sanders, 2011; McCabe & Sanders, 2012) that could indicate that there is rotation between the upper and lower torso in front crawl. Further, the changes in stroke rate associated with changes in swimming speed (Chollet, Chalies, & Chatard, 2000; Craig, Skehan, Pawelczyk, & Boomer, 1985; Schnitzler, Seifert, Ernwein, & Chollet, 2008; Seifert, Chollet, & Bardy, 2004) could influence the rate of change of hip roll angle and shoulder roll angle and, consequently, produce different rates of change of torso twist. Swimmers may therefore vary their patterns of body rotation depending on the distance over which they are competing. Considering the association between torso muscle activity and the magnitude and speed of rotation between the upper and lower torso (Kumar, Narayan, & Zedka, 1996; Marras & Granata, 1995), the demands on the torso muscles could be related to differences in body rotation about the longitudinal axis at different swimming speeds. The differences in the range and rate of change of hip roll, shoulder roll, and torso twist at different front crawl speeds, however, have never been reported.

Longitudinal body rotation in front crawl could be influenced by actions from the flutter kick. It has been hypothesised, for example, that the motions of the lower limbs in the flutter kick may produce reaction torques at the hips that dampen hip roll (Sanders & Psycharakis, 2009). The dampening effect of the flutter kick has been described by several authors (McCullough et al., 2009; Sanders, 2007; Vorontsov & Rumyantsev, 2000) and likely involves activity of the torso muscles; however, the relationships between lower limb movements and longitudinal rotation in front crawl swimming have not been empirically investigated. This produces a barrier to our understanding of the influence of the flutter kick on the requirements of the torso muscles during front crawl swimming. Therefore, research into the characteristics of flutter kick kinematics and longitudinal torso rotation at different swimming speeds is required to develop a better understanding of the demands on the torso muscles in front crawl swimming.

An estimation of the neural input to the torso muscles can be obtained using underwater electromyography (EMG). By relating the EMG profiles of the torso muscles to the patterns of longitudinal torso rotation of experienced front crawl swimmers, the contribution of the torso muscles to front crawl swimming can be better understood.

A clear description of body rotation about the longitudinal axis and torso muscle activity in front crawl swimming would provide an evidence-based foundation for the development of guidelines for swimming-specific dry-land strength training. The diverse roles the torso muscles may play in front crawl swimming could be better understood from analyses of movement patterns at different front crawl speeds. This would provide context to the range of demands placed on the torso muscles for coaches and swimmers. The demands on the torso muscles in front crawl can be inferred from the biomechanical characteristics of experienced swimmers. Exercises could then be designed based on the demands of front crawl swimming to maximise the probability that adaptations to dry-land strength training transfer to front crawl performance.

Purpose

The purpose of this thesis was to establish the roles of the torso muscles during front crawl swimming from analysis of rotation about the body’s longitudinal axis and torso muscle activity data during sprint and middle-distance front crawl.

Objectives

1. Identify patterns in the range and rate of change of hip roll, shoulder roll, and torso twist.
2. Investigate the impact of the flutter kick on body rotation about the longitudinal axis.
3. Explore the relationships between torso muscle activity and body rotation about the longitudinal axis.
4. Develop swimming-specific guidelines for dry-land strength training of the torso muscles from kinematic and muscle activity patterns in front crawl swimming.

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CHAPTER 2:

Literature Review

This chapter reviews current knowledge of longitudinal body rotation in front crawl swimming, propulsion from the flutter kick in front crawl, effects of the flutter kick on longitudinal body rotation, and torso muscle activity in front crawl swimming. Lastly, techniques for measuring myoelectric activity of the torso muscles and special considerations for underwater electromyography are reviewed.

Longitudinal Body Rotation in Front Crawl Swimming

A common method for representing shoulder roll and hip roll is to calculate the angle between the horizontal axis perpendicular to the intended swimming direction and vectors connecting the shoulders and hips, respectively, projected onto the vertical plane perpendicular to the swimming direction (Psycharakis & Sanders, 2010). Shoulder roll and hip roll can be calculated from 3D reconstruction of digitised body landmarks from 2D video or from 3D motion capture data. Shoulder roll and hip roll tend to follow a sinusoidal pattern as the body rolls from one side to the other and back again. For each stroke cycle (e.g. from the moment of hand entry into the water to the subsequent moment of entry of the same hand), shoulder roll and hip roll complete approximately one cycle of rotation from one side to the other (Figure 2-1). Shoulder roll and hip roll have been reported as a maximum angle to the left and/or right sides (Cappaert, Pease, & Troup, 1995; Yanai, 2003) or as a sum of the range of rotation from one side to the other, referred to as the range of or total shoulder roll and total hip roll (Figueiredo, Sanders, Gorski, Vilas-Boas, & Fernandes, 2013; McCabe et al., 2011; McCabe & Sanders, 2012; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009).

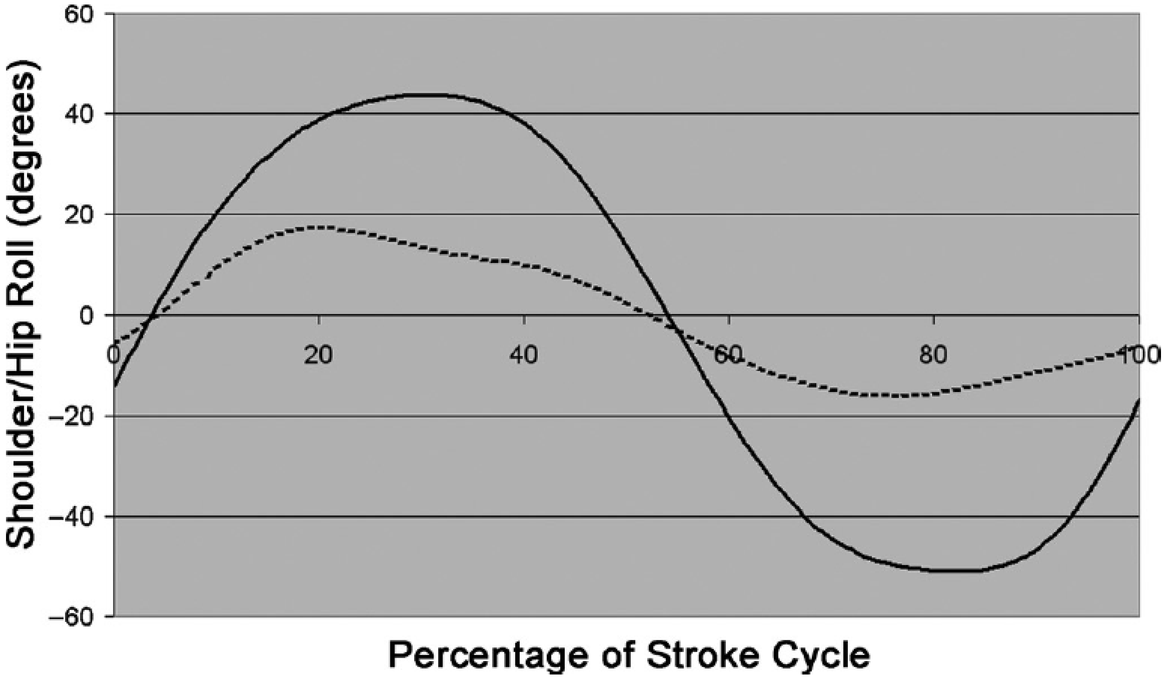

Figure 2-1. Shoulder roll (solid line) and hip roll (dashed line) patterns of national and international front crawl specialists over one arm stroke cycle in the first 50m a 200m maximal front crawl test reported by Psycharakis and Sanders (2008). Positive and negative values along the vertical axis represent shoulder and hip roll to the counter-clockwise and clockwise sides, respectively, when viewing the swimmer head-on. The stroke cycle began at the moment the right hand entered the water (zero on the horizontal axis) and ended at the moment of the subsequent entry of the right hand (100 on the horizontal axis).

Shoulder roll and hip roll at different swimming speeds

Figure 2-2 shows the relationship between total hip roll and swimming speed using data compiled from five studies of national and international level male front crawl swimmers (McCabe et al., 2011; McCabe & Sanders, 2012; Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009). The studies investigated front crawl at sprint pace, 200m pace, or 400m pace and swimming velocity ranged from 1.4 m/s to 1.8 m/s across all five papers. While acknowledging the limitations of combining cross-sectional data from different studies, the inverse relationship between total hip roll and swimming speed, denoted by the line-of-best-fit, suggests that swimmers tend to roll their hips less as swimming speed increases. For example, McCabe and Sanders (2012) reported total hip roll of 51 degrees at

1.4 m/s during a 400m front crawl test while McCabe et al. (2011) observed total hip roll of 36 degrees at 1.8 m/s during a maximal 25m sprint using the same population of swimmers. Data from the studies by Psycharakis and Sanders (2008) and Sanders and Psycharakis (2009) were measured from each lap of a simulated 200m front crawl race and therefore changes in total hip roll in these studies could have been influenced by fatigue. Nonetheless, total hip roll appears to decrease as swimming speed increases.

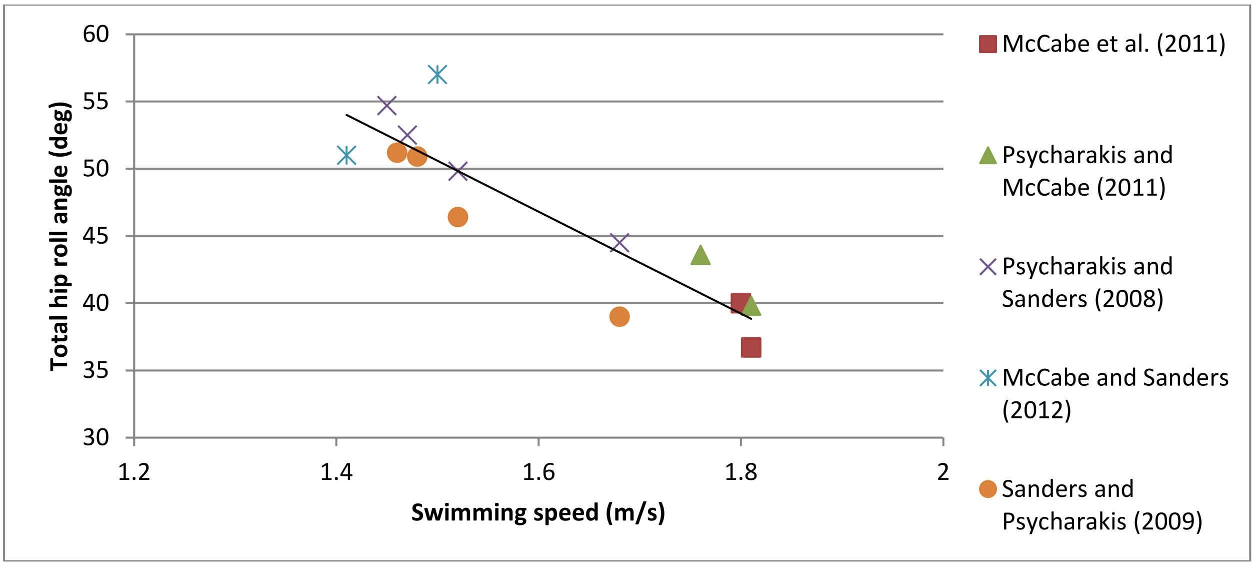

Figure 2-2. Relationship between total hip roll and swimming speed using a line-of-best-fit based on data from five studies.

Total shoulder roll does not seem to change as much as total hip roll as swimming speed increases according to data from the same five studies. The line-of-best-fit in Figure 2-3 suggests total shoulder roll remains relatively constant for swimming speeds from 400m pace to sprint pace among national and international level front crawl swimmers. Across the five studies, total shoulder roll remained between 103 to 111 degrees.

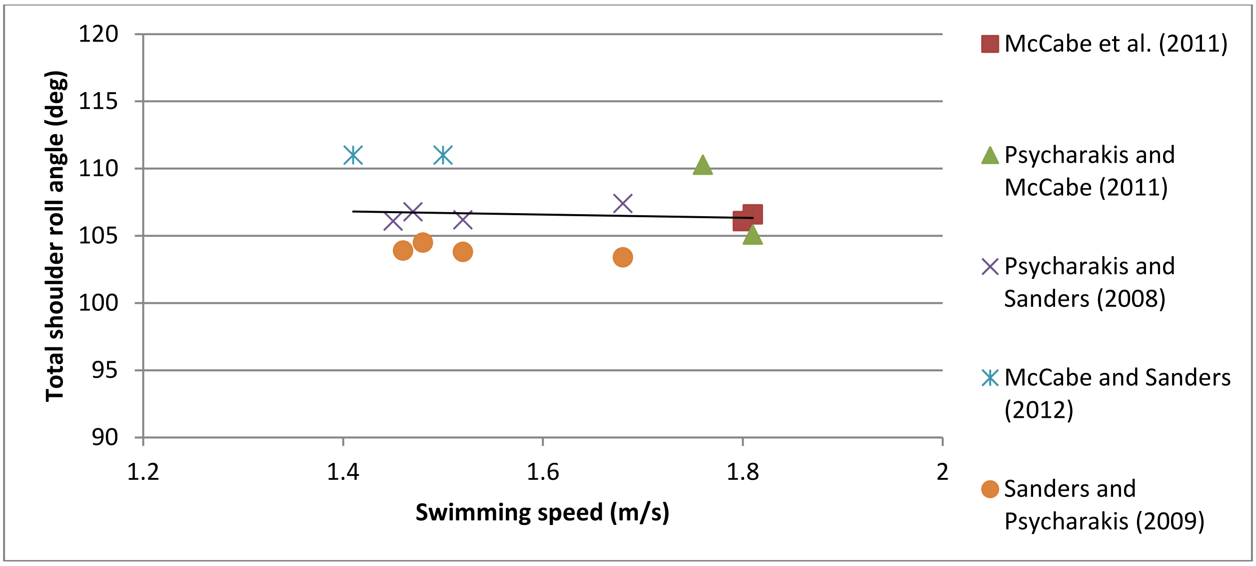

Figure 2-3. Relationship between total shoulder roll and swimming speed using a line-of-best-fit based on data from five studies.

Though the data in Figure 2-2 and Figure 2-3 may indicate that changes in hip roll between swimming speeds could be greater than the changes in shoulder roll between swimming speeds, we can only speculate when comparing cross-sectional data from studies that involved different groups of swimmers. While the characteristics of shoulder and hip roll have been examined at different swimming speeds, the effects of swimming speed on shoulder roll and hip roll have never been examined in a single study using the same participants. Research into the patterns of shoulder roll and hip roll at different swimming speeds is required.

Torso twist

Differences in the relative magnitude and/or timing of shoulder roll and hip roll are likely to cause ‘twist’ within the torso. A relative difference between shoulder and hip roll is likely produced by rotation between the upper and lower torso about the body’s longitudinal axis. The term ‘torso twist’ can therefore be used to describe the relative difference between 1) shoulder roll and hip roll and 2) upper torso rotation and lower torso rotation at any instant of the front crawl stroke.

Relative differences between shoulder and hip roll have been described in scientific literature. Yanai (2001b), for instance, observed similar phase angles of shoulder roll and hip roll, but greater magnitude of shoulder roll than hip roll, in swimmers swimming at “submaximal sprinting speed” of 1.6 m/s. Yanai (2001b) concluded that body roll can be described as a roll of the entire body as well as a twist within the torso. In the men’s 100m freestyle event at the 1992 Olympics, Cappaert et al. (1995) observed that swimmers in the slower preliminary heats (average swimming speed: 1.87 m/s) rolled their shoulders and hips in opposite directions while swimmers in the faster heats (average swimming speed: 2.01 m/s) rolled their shoulders and hips in the same direction. Cappaert and colleagues proposed that larger relative differences in shoulder and hip roll could increase active drag due to an increase in frontal surface area facing the swimming direction. While increases in frontal surface area could negatively affect swimming performance (Zamparo, Gatta, Pendergast, & Capelli, 2009), there was no direct association between relative differences in shoulder and hip roll and swimming speed in the study by Cappaert et al. (1995). Psycharakis and Sanders (2008) identified four different profiles in the timing of shoulder roll and hip roll at 200m pace (average swimming speed: 1.53 ± 0.06 m/s): symmetric shoulder and hip roll, asymmetric shoulder and hip roll, asymmetric shoulder and hip roll on the preferred breathing side only, and asymmetric shoulder and hip roll on the non-preferred breathing side only. The findings by Psycharakis and Sanders (2008) indicate that differences in torso twist can exist between swimmers swimming at the same pace. While the magnitude and timing of shoulder roll and hip roll in front crawl have been investigated at different swimming paces, differences in torso twist between swimming paces has never been investigated, producing uncertainty of torso twist patterns at different swimming paces.

Propulsion from the Flutter Kick in Front Crawl

The flutter kick contributes to front crawl swimming performance by generating fluid forces that are likely to produce a) forward movement or propulsion (Gatta, Cortesi, & Di Michele, 2012; Wei, Mark, & Hutchison, 2014) and b) body rotation (e.g. to influence body roll (Yanai, 2001b, 2003) and horizontal body alignment (Maglischo, 2003; Yanai, 2001a)). However, little is known about how the lower limbs generate fluid forces in front crawl swimming, limiting the accuracy of estimating the magnitude of the flutter kick's contribution to front crawl swimming (Andersen & Sanders, 2018). The following systematic review explored the generation of fluid forces from the flutter kick using findings from studies of propulsion from the dolphin kick. The review was published in the Journal of Sports Sciences in January 2018 as:

Andersen J.T., Sanders R.H. (2018) A systematic review of propulsion from the flutter kick – What can we learn from the dolphin kick? *Journal of Sports Sciences, 36*(18), 2068-2075.

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A systematic review of propulsion from the flutter kick – What can we learn from the dolphin kick?

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ABSTRACT

Propulsion, one of the most important factors in front crawl swimming performance, is generated from both the upper and lower limbs, yet little is known about the mechanisms of propulsion from the alternating movements of the lower limbs in the flutter kick (FK). The purpose of this systematic review was to review the literature relating to the mechanisms of propulsion from FK in front crawl. There was limited information about the mechanisms of propulsion in FK. Since movements of the lower limbs are similar between FK and the dolphin kick (DK), mechanisms of propulsion from DK were reviewed to better understand propulsion from FK. Recent evidence suggests that propulsion in DK is generated in conjunction with formation and shedding of vortices. Similar vortex structures have been observed in FK. Visualisation and simulation techniques, such as particle image velocimetry (PIV) and computational fluid dynamics (CFD), are non-invasive tools that can effectively model water flow without impacting swimming technique. These technologies allow researchers to estimate the acceleration of water and, consequently, the propulsive reaction forces acting on the swimmer. Future research should use these technologies to investigate propulsion from FK.

ARTICLE HISTORY
Accepted 20 January 2018

KEYWORDS
Propulsion; human swimming; flutter kick; vortex; dolphin kick

Introduction

Propulsion is considered one of the most important factors in front crawl swimming performance (Toussaint & Truijens, 2005). Though the upper limbs produce greater propulsion than the lower limbs (Miller, 1975), the lower limbs also play an important role (Deschodt, Arsac, & Rouard, 1999). Much less is known about the mechanisms of propulsion from the lower limbs than from the upper limbs and there is conflicting evidence regarding the magnitude of the contribution of the lower limbs to front crawl swimming. To fully understand how to maximise propulsion in front crawl, the mechanisms of propulsion from the lower limbs using the flutter kick (FK) must be explored further.

Newton's Third Law of Motion accounts for forward propulsion from hydrodynamic reaction forces when water masses are accelerated backwards (Counsilman & Counsilman, 1994, pp. 7–8; Toussaint, Hollander, Van Den Berg, & Vorontsov, 2000). Propulsion from the upper limbs is easy to conceptualise because the hands move predominantly backwards and reaction forces are therefore directed forwards. In contrast, the lower limbs in FK move in an alternating "up-and-down" arching trajectory almost perpendicular to the swimming direction of the internal reference frame (i.e. with respect to the swimmer). There is continuous forward motion in front crawl that moves the lower limbs forwards throughout the kick cycle, not backwards, with respect to the inertial reference frame (i.e. with respect to the pool). Thus, it is difficult to conclude that water is accelerated backwards from the actions of the lower limbs in the same way as the arms at typical front crawl swimming velocity (e.g. 1.34 to 1.57 m·s^{-1} across 200m (Figueiredo, Nazário, Cereja, Vilas-Boas, & Fernandes, 2011).

Rotating masses of water, known as vortices (Pai & Hay, 1988), can also accelerate water backwards and, in doing so, produce propulsive reaction forces. As the limbs move through the water, vortices are generated. These vortices are then "shed" to the surrounding water when the limbs change direction and propulsion is generated (Matsuuchi et al., 2009; Takagi et al., 2014). In undulatory kicking (referred to as dolphin kicking hereafter), a vortex ring is left in the swimmer's wake when the feet finish the downbeat and begin the upbeat (B. Ungerechts, 1985). Water is accelerated backwards from the vortex ring and, in accordance with Newton's Third Law, momentum is conserved because the swimmer moves forward (Arellano, Pardillo, & Gavilán, 2002; Von Loebbecke, Mittal, Mark, & Hahn, 2009). Rotating masses of water have been observed in the wake of FK that are shed backwards from the shanks and feet (Arellano, 1999) despite the forward movement of the lower limbs in the inertial reference frame. Considering the similarities between FK and the dolphin kick (DK) (Arellano et al., 2002) and evidence for vortex propulsion from other swimming motions (e.g. hand and forearm (Matsuuchi & Muramatsu, 2011; Takagi, Nakashima, Ozaki, & Matsuuchi, 2014) and breaststroke kick (Arellano, 1999), there is a need for analysis of the role of rotational water flow in the mechanisms of propulsion of FK.

FK is taught from an early age in swimming (Cureton, 1930) and kicking drills often comprise a significant portion of training programs (Konstantaki & Winter, 2007). The contribution of

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FK to front crawl propulsion, however, varies depending on the method of measurement. For example, researchers have attributed approximately 10% of swimming velocity to lower limb motions when comparing “arms only” swimming to free swimming (Deschodt et al., 1999; Gourgoulis et al., 2014) while others have measured a much greater relative contribution of the legs (approximately 30%) to force production in tethered swimming (Morouco, Marinho, Izquierdo, Neiva, & Marques, 2015). The limited understanding of the mechanisms of propulsion has led to an uncertainty with regard to how much time should be allotted to training FK. The assumptions inherent in the methods used to estimate propulsion must be considered carefully in order to draw accurate conclusions that are valid for competition swimming.

The purpose of this systematic review was to review literature relating to the mechanisms of propulsion from the FK in front crawl swimming. Gaps in the literature would also be highlighted that must be addressed to improve understanding of the mechanisms of propulsion from the lower limbs with additional insights gained from review of mechanisms of propulsion from DK.

Methods

Databases, keywords and search strategy

A comprehensive systematic search of the literature was conducted to gather research relating to the mechanisms of propulsion from the legs. Scientific research in English was examined between 1931 and July 2017 from five international databases (Ovid MEDLINE, SPORTDiscus, Pubmed, Web of Science, and Embase). The keywords in the “Swim” column of Table 1 were combined into a single term. This was then joined with each of the terms in the “Components” column (i.e. using AND), individually, in MEDLINE. Searches in the other databases were performed with this process. Titles and abstracts from proceedings of the International Symposia for Biomechanics and Medicine in Swimming, the most prominent swimming research conference in the world, were also included in the search.

Inclusion and exclusion criteria

The inclusion criteria specified that publications were peer-reviewed, either from an academic journal or a prominent scientific conference. There were no age restrictions of participants. We wanted to incorporate as much information as possible because, to our knowledge, no review of the mechanisms of propulsion of FK currently exists. Our initial search retained studies that described and estimated propulsion from the legs in front crawl swimming alone; however, limited research was found that examined the mechanisms of propulsion from FK. Therefore, we broadened our inclusion criteria to include investigations of the mechanisms of propulsion from DK, since leg movements are similar in both skills (Arellano et al., 2002), and repeated the search and review process. This allowed for a more comprehensive analysis of propulsion from lower limbs in swimming. Studies were excluded that involved simulated swimming on dry land, fin swimming, aquatic activities that did not involve FK or DK (e.g. breaststroke and breaststroke kicking, synchronised swimming, etc.), injured swimmers, or swimmers with cognitive impairments.

Table 1. Combinations of keywords for searches of the databases.

Swim	Components
swim.mp OR front crawl.mp OR frontcrawl.mp OR front-crawl.mp	kick.mp propulsion.mp exp Lower Extremity/OR lower limb.mp

Study selection

The search returned 7408 articles after duplicates were removed using EndNote (EndNote X7.5). Titles and abstracts were reviewed for investigations of the mechanisms of propulsion from FK and DK by one author (JA). In addition to the studies that were retained from the search, four book chapters (Colwin, 2002; Maglischo, 2003; B. Ungerechts, 1985; Vorontsov & Rumyantsev, 2000) and one article (Stefan Hochstein, Pacholak, Brücker, & Blickhan, 2012) were selected from the reference lists of the included studies.

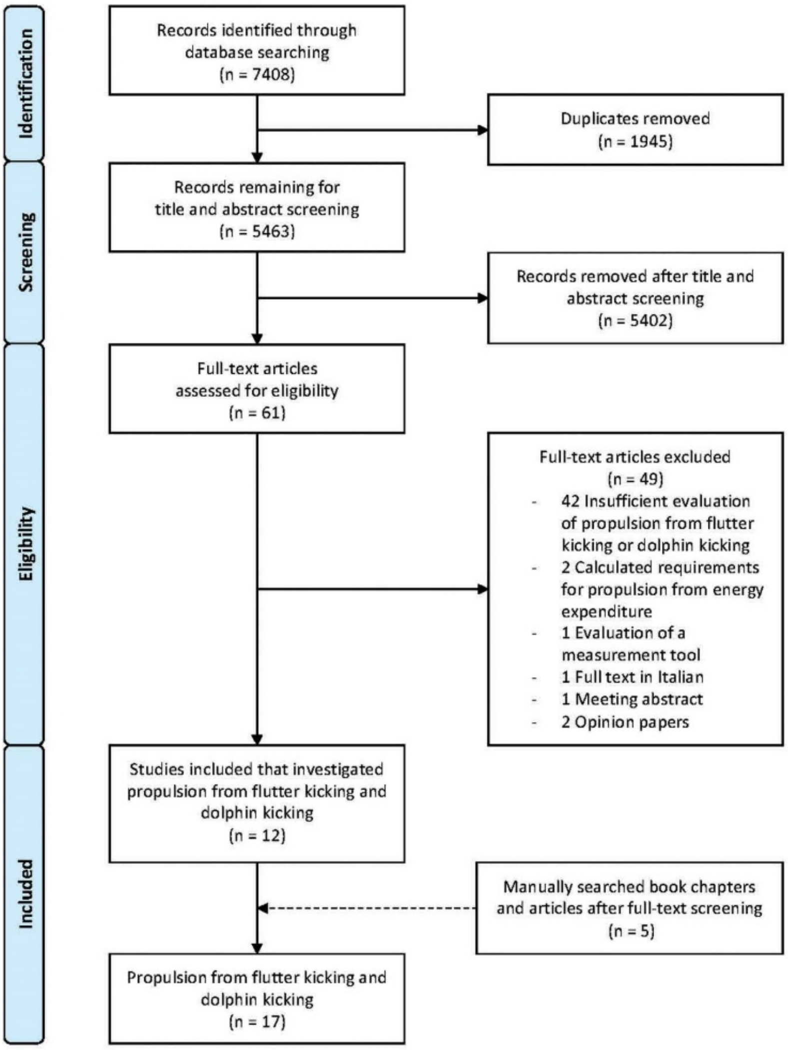
Results

Figure 1 shows the PRISMA flow diagram of the selection process. Title and abstract screening retained sixty-one full text articles that were assessed for eligibility. Forty-nine were excluded for the reasons listed in Figure 1. Twelve articles met all of the eligibility criteria from the systematic search and were included in this review.

Propulsion from the flutter kick

Two book chapters (Maglischo, 2003; Vorontsov & Rumyantsev, 2000) described propulsion generation from FK in terms of acceleration of masses of water backwards, but were not supported by reference to empirical investigations. Authors of one chapter reasoned that because lower limb movements in FK are perpendicular to the swimming direction, the propulsion generated is limited (Vorontsov & Rumyantsev, 2000). The author of the other chapter proposed that only the downbeat of FK has the capacity to generate propulsion because the feet push water backwards during this phase. The author also stated that the upbeat of FK likely produces resistive drag because knee flexion during the upbeat moves the shank towards the swimming direction, thereby producing reaction forces that are directed backwards (Maglischo, 2003, pp. 117–119).

Lyttle, Keys, Cheng, and Blanksby (2014) used a computational fluid dynamics (CFD) model to predict the propulsive and resistive forces acting on different body segments during FK at the water’s surface and 1.5m below it. The authors observed more propulsive thrust from FK at the water’s surface compared to the submerged simulation; however, for the period of time that the feet and calves lost contact with the water in the surface condition, propulsion was greater in the submerged condition. No other conclusions were made about the mechanisms of propulsion.



From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement.* PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

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Figure 1. PRISMA flow diagram of study selection process.

Evidence of vortex formations from FK was reported in one article that summarised the results of several studies (Arellano, 1999). In one study, swimmers passed through a "bubble wall", generated by air pushed through a submerged horizontal line with holes every 5cm, showing rotational water flow produced by FK in the swimmer's wake.

Propulsion from the dolphin kick

More studies were found for the mechanisms of propulsion from DK than from FK. Propulsion in DK was generally attributed to forward-directed reaction forces generated by water pushed backwards either directly from the lower limbs or concurrently with vortex shedding.

Basic flow visualisation

In early studies, basic visualisation techniques, such as injecting dye (Colman, Persyn, & Ungerechts, 1999; B. Ungerechts, 1985) or air bubbles (Arellano, 1999; Arellano et al., 2002; Arellano, Terres-Nicol, & Redondo, 2006) into the water from a tube attached to the swimmers' shank or big toe, were used to observe water flow in DK. The dye and bubble traces revealed vortices shed into the swimmers' wake when the feet reversed direction: a large vortex was shed at the end of the downbeat and a smaller vortex was shed at the end of the upbeat.[1] These vortices were staggered

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[1] For the purposes of this review, "downbeat" and "upbeat" of a kick are with reference to a swimmer positioned horizontally faced down. Authors of one study used a model on its back that kicked faced up (Cohen et al., 2012).

and rotated in opposite directions. Colman et al. (1999) connected visualisations of vortex structures from dye injections to hip velocity changes in DK. Throughout the downbeat, water flow illuminated by the dye moved backwards from the ankles at the same time that the hips accelerated forward. A rotating vortex remained in the swimmer's wake at the end of the downbeat. At the end of the upbeat, a vortex was observed at the feet during knee flexion, just prior to hip acceleration. The authors of the two dye injection studies (Colman et al., 1999; B. Ungerechts, 1985) concluded that swimmers "push-off" from these vortices to generate propulsion.

A series of studies by Arellano and colleagues (Arellano, 1999; Arellano et al., 2002, 2006) has led to the proposal that propulsion is generated in DK from the reaction to a backward-directed jet created between staggered vortices due to the momentum of their opposite rotations, similar to a Karman vortex street in fish swimming. By injecting air bubbles into the wake, Arellano and his colleagues observed that production of counter-rotating vortices coincided with the end of the upbeat and downbeat. Ungerechts, Persyn, and Colman (2000) also described how propulsion may be generated in DK from an impulse reaction to a "jet stream" generated by the opposite rotations of the staggered vortices.

A third mechanism was theorised from propulsion in fish that involved the "annihilation", or stopping the rotation, of vortices (Ungerechts, Persyn, & Colman, 1999). B. Ungerechts et al. (2000) explained that if a vortex was not shed into the swimmer's wake when the feet reverse direction, the feet may kick into the vortex and stop the rotational flow. The vortex' momentum would be transferred to the swimmer to propel them forward.

In his swimming text, Colwin (2002, p. 96) described the "fling-ring" mechanism for propulsion from DK at the water surface based on his own observations. He proposed that a maximum effort downbeat causes water to circulate in vortices around each foot. These vortices join to form a vortex ring around both feet. At the end of the downbeat, the vortex ring is shed into the swimmer's wake, producing a propulsive reaction force.

Advanced flow visualisation and simulation

A "propulsive jet" was observed during a DK using particle image velocimetry (PIV) (Miwa, Matsuuchi, Shintani, Kamata, & Nomura, 2006). PIV is a technique in which water particles are illuminated with a laser and their motion captured as a two-dimensional image with a specialised camera. In contrast to the jet stream in a Karman vortex street (Arellano et al., 2002), the propulsive jet was oriented downwards and backwards. Further, the jet was located between two counter-rotating vortices that appeared in the swimmer's wake after the downbeat alone. The authors (Miwa et al., 2006) postulated that these vortices comprised part of the three-dimensional vortex ring described by Colwin (2002).

CFD simulation of DK in one study revealed a single vortex ring shed at the end of the downbeat into the swimmer's wake (Figure 2, left) (Von Loebbecke et al., 2009). Water flow was directed backwards by the change in momentum of the rotating masses of water (Figure 2, middle). When viewing a two-dimensional slice through the vortex ring from the side, two counter-rotating vortices were observed. As shown in the right-most picture in Figure 2, water was accelerated backwards as a "jet stream", creating a forward directed reaction force on the swimming model (Von Loebbecke et al., 2009). The movement of water as a "jet" between counter-rotating vortices was also observed in a study using PIV (S. Hochstein & Blickhan, 2011). CFD modelling (Stefan Hochstein et al., 2012) showed the development of a jet in the centre of a vortex ring as well. Vortex rings were also observed (Cohen, Cleary, & Mason, 2012) at the end of both the downbeat and upbeat of DK using smoothed particle hydrodynamics (SPH – a type of CFD modelling). The shedding of these vortices coincided with propulsive peaks in the kick cycle in simulated towing of a swimming model performing DK.[2]

Another potential source of propulsion in DK, "vortex re-capturing", was explained in a series of three studies using PIV (S. Hochstein & Blickhan, 2011), PIV and CFD (Stefan Hochstein et al., 2012), and CFD (Pacholak, Hochstein, Rudert, & Brücker, 2014) and contributed to propulsion in two ways.

In the first way, vortex re-capturing begins during the downbeat when a vortex is produced just caudal to the dorsal aspect of the knee. The vortex rotates clockwise when viewing the swimmer from the right (Figure 3(A–C)). During the sub-

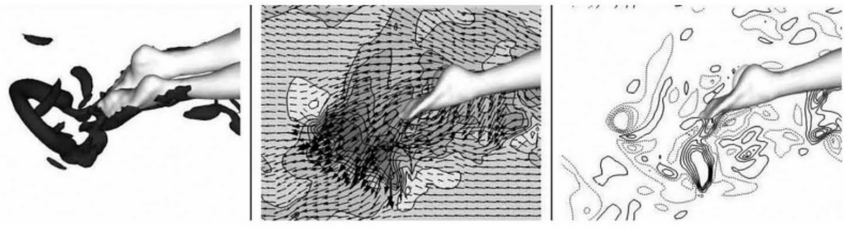

Figure 2. When the feet change direction at the end of the downbeat, a vortex ring is shed into the swimmer's wake (left). CFD modelling shows the movement of water particles in a propulsive jet that is directed back and down (middle). Propulsion is created by the conservation of momentum in the middle of the vortex ring (right – counterclockwise rotational flow is denoted by solid lines, clockwise rotational flow is denoted by dotted lines) (Von Loebbecke et al., 2009). Reprinted with permission from Taylor & Francis Ltd: www.tandfonline.com.

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[2] The authors of this study (Cohen et al., 2012) used a model of a swimmer kicking on its back, but the term "downbeat" in the current review is with reference to the hip flexion/knee extension phase and "upbeat" refers to the hip extension/knee flexion phase of the dolphin kick.

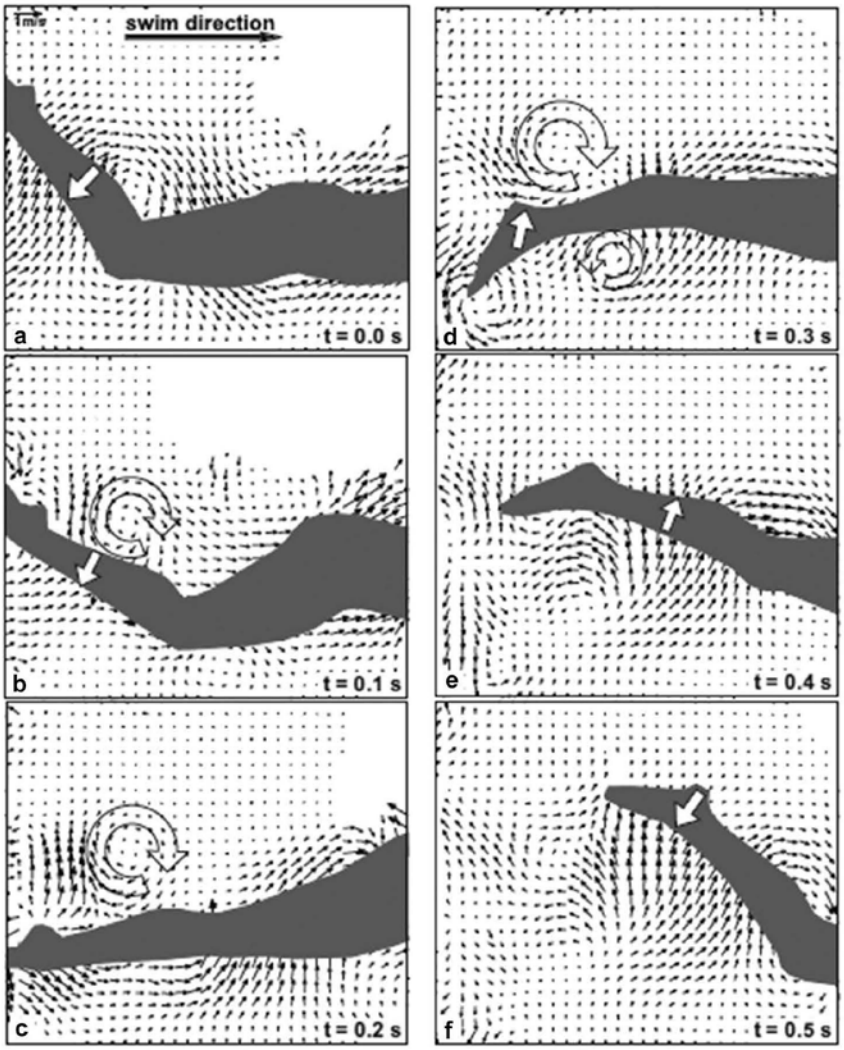

Figure 3. Rotating water vortices caused by the downbeat (A-C) and the subsequent upbeat (D-F) of undulatory kick. The straight white arrow shows the direction of movement of the legs. The larger rotating arrow denotes the large vortex produced by the downbeat that contributes to propulsion from the upbeat of the kick. A smaller vortex is produced by the upbeat, denoted by the small rotating arrow (S. Hochstein & Blickhan, 2011). Reprinted with permission from Elsevier.

sequent upbeat, the shanks kick into the vortex (Figure 3(D–F)). S. Hochstein and Blickhan (2011) proposed that propulsive thrust would increase as a result of the destruction of the vortex because the swimmer could "reuse" the energy of the previously shed vortex, similar to vortex annihilation (Ungerechts et al., 1999; B., 2000). In subsequent studies (Stefan Hochstein et al., 2012; Pacholak et al., 2014), CFD modelling produced three-dimensional vortex formations that were similar to those observed in the PIV images in Figure 3. The CFD simulation in one study (Pacholak et al., 2014) showed an increase in forward thrust when the feet struck the vortex during the upbeat. The authors concluded that the interaction between the upwards movement of the feet and the rotational direction of this vortex (Figure 3(D,E)) resulted in a reaction force in the swimming direction.

In the second way, "flow preformation", propulsion could be produced by "recapturing" caudally moving vortices generated by movements of the arms and shoulders. At the end of a downbeat, the vortical structures from flow preformation joined the vortex shed from the feet, re-capturing the kinetic energy given to the water by the undulations of the upper body. After six kick cycles, this process increased the intensity of the vortices shed from a downbeat at the feet and propulsion increase by 8% compared to the second kick cycle (Stefan Hochstein et al., 2012; Pacholak et al., 2014).

Discussion

The purpose of this systematic review was to review the literature relating to the mechanisms of propulsion from the legs in FK. There was a paucity of investigations of the mechanisms of propulsion from the legs in FK. Studies of DK provided insight into the mechanisms of propulsion from FK. Propulsion was produced by forward directed reaction forces that coincided with changes in water flow from the swimmers in all of the studies found in our search.

Vortices and propulsion in the flutter kick

Recent visualisation and simulation technologies have assisted investigations into water flow associated with propulsion in swimming. For example, CFD simulation of FK by Lyttle et al. (2014) indicated that differences in propulsion between the surface and submerged kicking conditions were attributable to periods of lost contact with the water in the surface condition. Considering the presence of vortex formations in FK (Arellano, 1999), the loss of propulsion in the surface kicking condition likely resulted from the destruction of the trailing vortices whereas these remained intact in the submerged condition. B. Ungerechts (1985) made a similar conclusion of DK in butterfly swimming, stating that the propelling effect of the kick is lowered when the feet break the water surface. This remains speculative, however, and more investigations are required to better understand the water flow and fluid forces from FK.

The mechanisms of propulsion from FK in front crawl can be further understood by applying principles used to explain propulsion from DK. Differences in proximity of the kick to the water surface, kinematics between the two kicks, and water flow from the cephalic regions of the body, however, must be considered. Swimmers can potentially gain propulsion from a propulsive jet with vortices shed by the downbeat of their flutter kick, similar to downbeat of DK. Vortices that generate a propulsive jet after the downbeat of FK would likely remain intact due to the depth at which they are shed. In DK, a jet was directed downwards from the toes and backwards with respect to the swimming direction (S. Hochstein & Blickhan, 2011; Stefan Hochstein et al., 2012; Miwa et al., 2006; Von Loebbecke et al., 2009). Assuming vortices are shed in a similar fashion in FK, the energy transferred to the water in the jet would produce propulsion.

The Karman vortex street observed in DK (Arellano et al., 2002), on the other hand, is less likely in front crawl since vortices shed from the upbeat of FK are destroyed when they reach the water surface (Lyttle et al., 2014). The vortex at the end of the upbeat of DK that coincided with hip acceleration observed by Colman et al. (1999) is also unlikely to form from the upbeat of FK for the same reason. A true fling-ring mechanism would not apply to the downbeat of FK either because the alternating movements of the legs would interrupt the flow formation described by Colwin (2002). However, there is likely interaction between vortex formations around either leg throughout FK cycle, though it is unknown whether vortices in FK join constructively, like the fling-ring mechanism, or destroy one another before propulsion is generated. Further research should be conducted to determine whether swimmers shed a pair of vortices/vortex ring after the downbeat of each leg in FK and if this coincides with changes in forward motion of the swimmer.

Though vortices shed by the upbeat of FK in front crawl have a limited capacity to generate propulsion, vortex re-capturing may still account for the propulsion potential of the upbeat of FK. The re-captured vortex in DK produced by knee extension of the downbeat (see Figure 3) (S. Hochstein & Blickhan, 2011; Stefan Hochstein et al., 2012) may be created far enough underwater in FK that the upbeat could strike it before it is altered by at the water-air interface. At the end of the downbeat of FK, the feet reach a depth of 0.26m to 0.48m below the water surface when they change direction (Figueiredo, Sanders, Gorski, Vilas-Boas, & Fernandes, 2013; Gatta, Cortesi, & Di Michele, 2012) and, consequently, shed vortices. The vortices generated by the downbeat of DK observed by S. Hochstein and Blickhan (2011) grew to 0.25x0.25m at the ankle. This would leave sufficient space below the water's surface for the vortex to remain intact, supporting the potential for vortex re-capturing in FK. Vortex re-capturing from flow preformation in front crawl also needs to be investigated. Just as waveforms about the transverse axis are transmitted caudally in DK and the butterfly stroke (Gavilán, Arellano, & Sanders, 2006; Sanders, Cappaert, & Devlin, 1995), rolling rhythms about the longitudinal axis are transmitted caudally in front crawl (Sanders & Psycharakis, 2009). Further research is required to determine the impact of the rolling rhythms in front crawl on flow preformation, as well as the formation of vortices around the legs in FK near the water surface to determine whether vortex re-capturing is feasible in front crawl.

The importance of considering water flow

The conclusion of Gatta et al. (2012) that propulsive force is dependent on swimming velocity must be considered when assessing the contribution of FK to propulsion. In other words, propulsive force depends on the water flow around the swimmer. Vortex formations change with increasing swimming velocity in DK (Pacholak et al., 2014) and the same likely occurs in front crawl. Methods of assessing propulsion that impede forward movement, such as tethered and semi-tethered swimming, are not representative of the forces in competition swimming (Martin, Yeater, & White, 1981; Yeater, Martin, White, & Gilson, 1981). The speed of the flow in tethered and semi-tethered swimming relative to the swimmer is less than in un-tethered swimming. If water flow relative to the swimmer and rotational flow are not considered, results will not be representative of normal swimming conditions. To effectively quantify propulsion, research methods must mimic normal swimming environments as much as possible. Further investigation of the influence of swimming velocities on flow characteristics will provide a better understanding of propulsion generation from FK.

Methods of measuring propulsion must also allow swimmers to freely manipulate water. For example, the production of vortices shed throughout the kicking cycle may be influenced by actions of the body and limbs "upstream" of the feet. Differences between "arms only" and free swimming have underlined the importance of an effective FK (Deschodt et al., 1999), but propulsion cannot be estimated effectively by comparing "arms only" swimming to swimming with the complete stroke because these methods inhibit swimmers from interacting with the water flow. Similarly, propulsion from FK cannot be accurately inferred by measurements of the arm stroke alone (e.g. using the MAD system (Hollander, De Groot, Van Ingen

Schenau, Kahman, & Toussaint, 1988) or calculating forces from hand speed (Gourgoulis et al., 2014). Methods that estimate propulsion from uninhibited movements of front crawl swimming, for example CFD and PIV, are more effective estimates than methods that isolate parts of the stroke.

Other recent technological developments show potential for more direct measurements of water flow. Methods used to obtain pressure differences of flow across a swimmer's hand (Takagi & Sanders, 2002; Takagi et al., 2014) are now being applied to the feet. Pressure sensors attached to a swimmer's foot were used to measure fluid forces acting on different parts of the foot in breaststroke (Tsunokawa, Nakashima, & Takagi, 2015) and eggbeater kicking (Kawai, Tsunokawa, Tsubakimoto, & Takagi, 2016). This approach takes into consideration the manipulation of water flow by a swimmer and provides valuable information about the changes in flow that can contribute to propulsion. An application of this technology for FK would improve understanding of the fluid forces involved in propulsion from the legs in front crawl.

Conclusions

This review identified a significant shortage of studies that provide insights into the mechanisms of propulsion from FK. It is difficult to model vortices in FK due to the water-air interface and the alternating leg motions. This could explain why research of the mechanisms of propulsion from FK is limited. While it is possible that the mechanisms of propulsion in DK may also apply to FK, research of the specific mechanisms acting in FK must be conducted. Investigations of the flow characteristics around the lower limbs in FK using modern technologies with realistic swimming conditions and velocities are required. This review highlighted the following questions to be addressed:

(1) How does the interaction between vortices from the upbeat of FK and surface waves influence propulsion generation in front crawl swimming?
(2) Is a propulsive jet formed by the downbeat of FK? If so, what is the relation between its formation and changes in swimming velocity?
(3) How do vortices around either foot in FK interact? What are the implications for propulsion generation?
(4) Does vortex re-capturing occur in FK?

Disclosure statement

No potential conflict of interest was reported by the authors.

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Effects of the Flutter Kick on Longitudinal Body Rotation

The flutter kick likely influences longitudinal body rotation from a combination of internal reaction torques from muscle forces used to generate the flutter kick and from external torques produced by hydrodynamic forces acting on the lower limbs. Evidence suggests that the rotation produced by the flutter kick can help swimmers control and facilitate longitudinal body rotation. For instance, muscle forces that drive movements of the lower limbs produce a reaction effect on the torso. Figure 2-4 is from the study by Yanai (2001b) in which he showed that the timing of a “strong” kick during submaximal front crawl swimming was executed just prior to peak shoulder roll in each of the swimmers he observed. The top graph shows total body torque (solid line) and the reaction torque of the lower limbs (dashed line) about the longitudinal axis. The reaction torque of the lower limbs acted in the direction opposite to shoulder roll angle in the bottom graph near the end of the strong kick (dark horizontal band). Yanai concluded that the swimmers he studied used the reaction of the strong kick to stop the body from rolling to one side, thereby controlling the amplitude of longitudinal body rotation. Yanai (2003) suggested in a later study that swimmers also use the flutter kick to help drive longitudinal body rotation. Yanai (2003) observed a three-cycle sinusoidal pattern in the total torque acting on the entire body that he attributed to torques from the alternating movements of the lower limbs in the six-beat flutter kick. He proposed that the three cycles of the six-beat flutter kick are timed such that the lower limbs generate longitudinal body rotation so that swimmers can direct more effort from the arm stroke to generate forward propulsion.

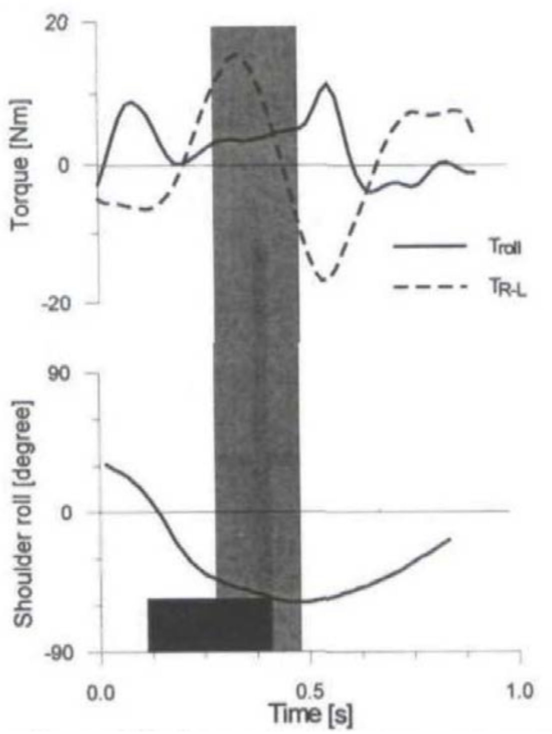

Figure 2-4. Data from Yanai (2001b) of one exemplar participant swimming front crawl. Positive values indicated rotation in the counter-clockwise direction and negative values indicate rotation in the clockwise direction when viewing the swimmer head-on. T_{roll} is the net torque acting on the torso and $T_{R\text{-}L}$ is the torque attributed to the reaction effect of lower limb acceleration acting about the longitudinal axis. The vertical grey band indicates the recovery phase of the arm stroke and the horizontal dark band is the duration of the "strong" kick.

The flutter kick has been described as having a "stabilising" effect on the torso from the rotation produced by movements of the lower limbs (Maglischo, 2003, pp. 117-119; McCullough et al., 2009; Sanders, 2007; Watkins & Gordon, 1983). The flutter kick may also help maintain body position in front crawl by producing rotation to oppose reaction forces generated by the arm stroke that can act to move the body out of alignment with the swimming direction (Vorontsov & Rumyantsev, 2000). While rotation from the lower limbs about the longitudinal axis may influence body rotation, the impact of rotation from the lower limb movements about the longitudinal axis on the upper limbs has never been studied. The relationship between rotation from the flutter kick and rotation from the arm stroke therefore remains speculative and requires further investigation.

Torso Muscle Activity in Front Crawl Swimming

Current and missing evidence

EMG data from the torso muscles can be combined with motion data to develop insights into the contribution of the torso muscles to front crawl swimming. Few studies exist, however, that reported findings of torso muscle activity during front crawl. According to a systematic review by Martens, Figueiredo, and Daly (2015), torso muscle activity during front crawl swimming has been investigated in just five research articles from three projects involving competitive swimmers (Clarys, 1985; Clarys, Massez, Van Den Broeck, Piette, & Robeaux, 1983; Ikai, Ishii, & Miyashita, 1964; Maes, Clarys, & Brouwer, 1975; Piette & Clarys, 1979). In the first ever study of torso muscle EMG in front crawl swimming, Ikai et al. (1964) observed a single peak in rectus abdominis activity from a university level swimmer and a triple peak in rectus abdominis activity from an Olympic swimmer. The timing of these peaks were not described with respect to swimming kinematics. Maes et al. (1975) later reported that one swimmer they measured had a single peak in rectus abdominis activity at the middle of the pull phase of the arm stroke while all other participants had no pronounced peaks in rectus abdominis activity. Data from the Brussels Swimming EMG Project (Clarys, 1988) revealed a double peak in rectus abdominis activity from two different swimmers, with one located between the push and pull phases of the arm stroke and the other prior to hand entry (Clarys, 1985; Clarys et al., 1983; Piette & Clarys, 1979). The differences in the patterns of rectus abdominis activity from the aforementioned studies is observable in Figure 2-5.

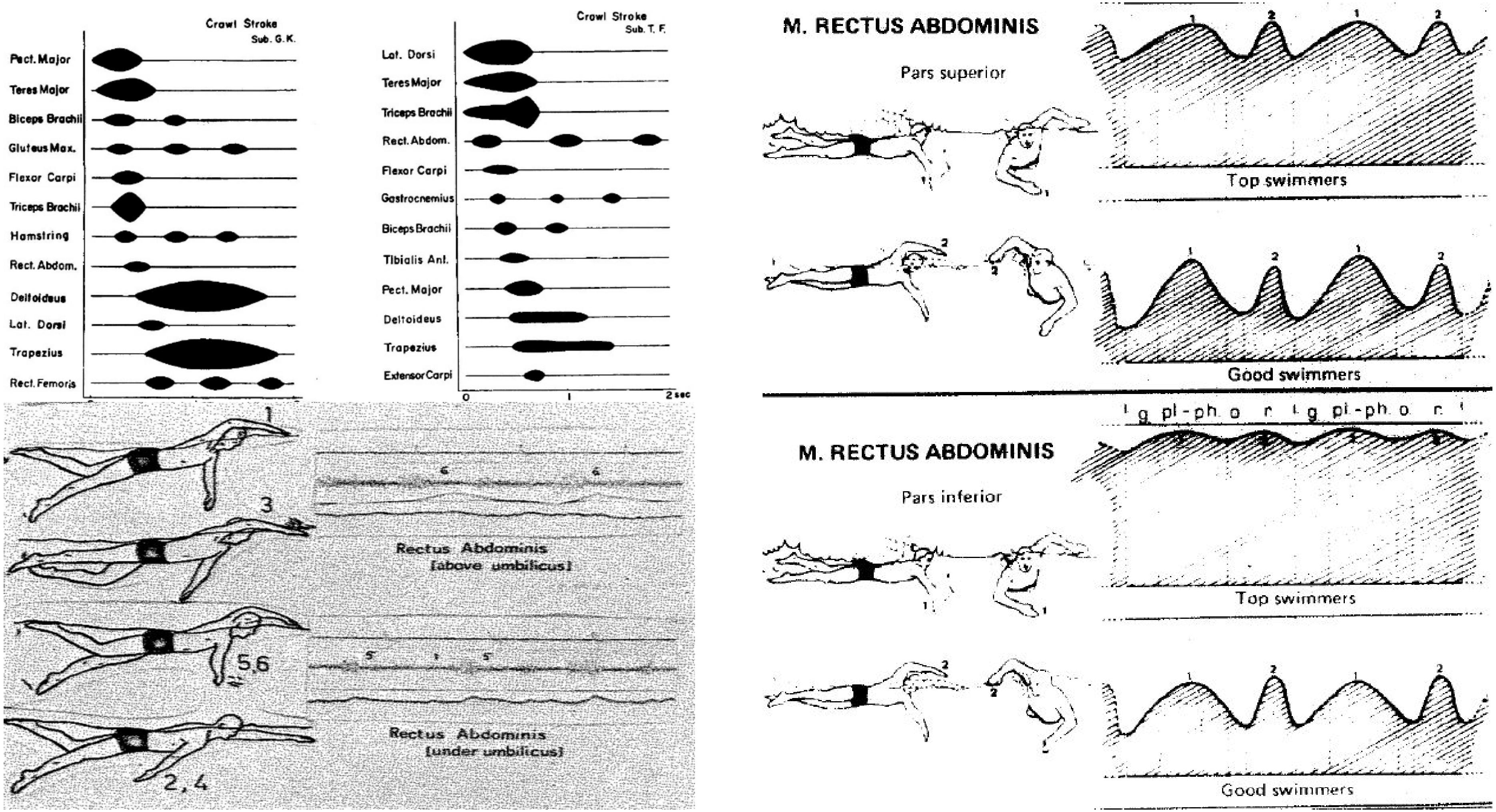

Figure 2-5. Rectus abdominis activity reported in the studies by Ikai et al. (1964) (top left), Maes et al. (1975) (bottom left), and Clarys (1985) (right). In the study by Ikai et al. (1964), muscle activity from the university level swimmer with a single peak in rectus abdominis is on the left labelled Sub. G.K. and the Olympic swimmer with a triple peak is on the right labelled Sub. T.F. The numbers in the pictures of the swimmers from the studies by Maes et al. (1975) and Clarys (1985) correspond to point in the stroke where the peaks in rectus abdominis activity occurred in the graphs immediately adjacent to each picture.

External oblique activity was also recorded in the Brussels Swimming EMG Project. Time series graphs (Clarys, 1985; Clarys et al., 1983) show a double peak per arm stroke cycle in external oblique: one peak occurred at the beginning of the pull phase and the other when the hand exited the water (Figure 2-6). However, the authors did not provide an explanation for the patterns of external oblique activity in the time series graphs and direct conclusions about the function of this muscle in front crawl swimming were not made.

Since publishing their systematic review, Martens and colleagues published studies to evaluate intra- (2015) and inter-individual (2016) variability of rectus abdominis EMG during front crawl swimming. The studies by Martens, Daly, et al. (2015) and Martens et al. (2016) revealed rectus abdominis activity was highly reliable when the left and right sides were compared within swimmers but patterns of activity were highly variable between swimmers. It was not, however, the purpose of these investigations to examine the associations between movement patterns and muscle activity. Rectus abdominis activity patterns in front crawl seems to vary between individual swimmers according to the few studies that have been conducted, but this cannot be confirmed or refuted due to a paucity of evidence. There is clearly a need for more research into torso muscle activity and how torso muscle activity relates to movement patterns in front crawl swimming.

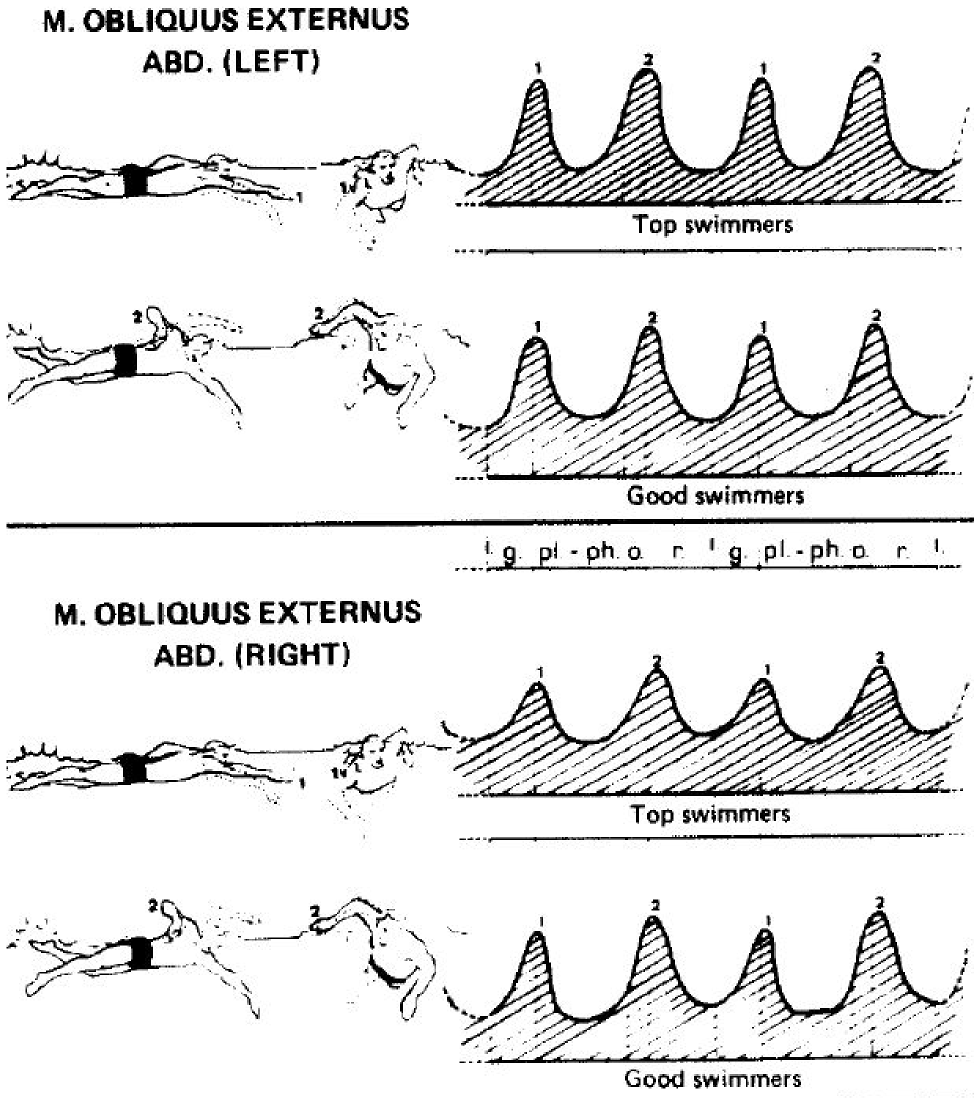

Figure 2-6. External oblique activity reported by Clarys (1985). The numbers in the pictures correspond to point in the stroke of the peaks in rectus abdominis activity in the graphs immediately adjacent to each picture.

Torso muscles and longitudinal body rotation in front crawl

Hypotheses can be developed about the roles the torso muscles may play in the body's rotation about longitudinal axis in front crawl swimming by examining the anatomy of the torso muscles and findings from studies of torso muscle function during torso rotation. The orientation of the internal and external oblique muscles diagonal to the spine results in moment arms that produce torques for generating rotation between the upper and lower torso (Gatton, Pearcy, & Pettet, 2001; McGill, Patt, & Norman, 1988). Findings from studies of isometric and dynamic torso twisting efforts in an upright posture (i.e. with minimal flexion/extension and lateral flexion) in standing (Marras & Granata, 1995; Pope, Andersson, Broman, Svensson, & Zetterberg, 1986) and in sitting (Kumar, Narayan, & Garand, 2003; Kumar et al., 1996) indicate that contraction of internal oblique generates rotation of the upper torso towards the ipsilateral side while external oblique contractions generate upper torso rotation towards the contralateral side. In addition to producing rotation between the upper and lower torso, the muscles of the torso are known to provide stability to the spine. Co-contraction of the left and right rectus abdominis and erector spinae in the lumbar and thoracic regions have been observed during twisting exertions of the torso, indicating a stabilising role of these muscles during torso twisting (Kumar et al., 2003; Kumar et al., 1996; Marras, Davis, & Granata, 1998; Marras & Granata, 1995; McGill, 1991; Pope et al., 1986).

Differences in the range and/or timing in shoulder roll and hip roll in front crawl swimming (Psycharakis & Sanders, 2008) may suggest there could be rotation between the upper and lower torso in front crawl that might result in a twisting motion of the torso. One of the roles of the torso muscles in front crawl swimming may therefore involve producing rotation between the upper and lower torso; however, other mechanisms, for example actions of the upper and lower limbs, can also produce rotation about the longitudinal axis in front crawl (Yanai, 2001b). Further, if the torso is twisting during front crawl, the torso muscles could play a spine stabilising role. The relationships between torso muscle activity and rotational kinematics of the torso need to be investigated to determine the roles of the torso muscles in longitudinal body rotation during front crawl swimming.

Selection of torso muscles to evaluate during front crawl

Torso motion and spine stability produced by the torso musculature is thought to be achieved through a coordination of torques produced by a range of torso muscles (McGill, 2001;

McGill, Grenier, Kavcic, & Cholewicki, 2003). Different torso muscles are likely to produce a similar pattern of activity due to the synergistic actions of the torso muscles (McGill et al., 2003). Therefore, it is possible that activity levels of select muscles of the torso may be used to represent activity of several torso muscles. McGill, Juker, and Kropf (1996) compared muscle activity from psoas major at the level of L3, quadratus lumborum, external oblique, internal oblique, and transverse abdominis using intramuscular EMG with muscle activity from rectus abdominis, external oblique, internal oblique, and erector spinae at the level of L3 using surface EMG. Participants in this study performed flexion, extension, lateral flexion, and twisting motions of the spine while EMG data were recorded. The authors observed similar patterns in muscle activity measured using intramuscular EMG and using surface EMG. McGill et al. (1996) concluded that surface EMG recordings adequately represent activity of the deep muscles of the torso when electrodes are placed over the following locations: rectus abdominis – 3cm lateral to the linea alba at the level of the umbilicus; external oblique – 15cm lateral to the linea alba at the level of the umbilicus; internal oblique – superior to the inguinal ligament and below the external oblique electrodes; and erector spinae – 3cm lateral to the spine at the level of L3. A limitation of the study by McGill et al. (1996) was that measurement of erector spinae activity was restricted to the level of lumbar spine. Differences in activity patterns of erector spinae have been observed during motions of the torso depending on the location of surface EMG electrodes. Kavcic, Grenier, and McGill (2004), for example, observed different patterns in lumbar and thoracic erector spinae activity across different exercises commonly used in rehabilitation of low back injuries. Therefore, activity from the lumbar and thoracic regions should be measured separately when investigating erector spinae torso muscle activity.

Latissimus dorsi has also been shown to contribute to spine stability (Kavcic et al., 2004; McGill, Karpowicz, Fenwick, & Brown, 2009); however, the primary function of latissimus dorsi in front crawl is likely to generate shoulder extension during the arm stroke (Pink, Perry, Browne, Scovazzo, & Kerrigan, 1991). Activity of latissimus dorsi during front crawl swimming therefore is unlikely to accurately reflect its role in producing spine stability for front crawl movements.

The use of surface EMG from one location to represent activity of more than one torso muscle has been used in biomechanical research. P. Marshall and Murphy (2003), for example, used internal oblique surface EMG data to represent the patterns of activity in transverse abdominis because of the interweaving anatomy of muscle fibres from these two muscles. The evidence from the literature presented above indicates that measurement of muscle activity from internal oblique, external oblique, rectus abdominis, lumbar erector spinae, and thoracic erector spinae using surface EMG could be used to investigate the roles of the torso muscles in front crawl swimming.

Best Practices for Obtaining EMG Data of the Torso Muscles

The task of obtaining EMG data of the torso muscles has unique challenges additional to the challenges of obtaining EMG data of limb muscles. These additional challenges must be addressed to maximise the quality and validity of the signal. Textbooks, scientific reviews, technical notes, and empirical articles that focused on EMG of the torso muscles were reviewed to determine best practices for measuring torso muscle activity using EMG. While fine-wire EMG can provide more specific information about myoelectric activity (Winter, 2009, pp. 251-255), the use of indwelling electrodes of the torso muscles during front crawl swimming has never been tested (Martens, Figueiredo, et al., 2015). This review will therefore focus solely on surface EMG of the torso muscles to maintain relevance for the current thesis.

Signal quality is determined by a researcher’s ability to minimise noise, artefact, and interference in the EMG signal (Clancy, Morin, & Merletti, 2002; Winter, 2009). EMG recordings can be confidently interpreted when there is a high signal-to-noise ratio. This ratio can be maximised by identifying unwanted signals that do not represent electrical activity of the muscle of interest and taking steps to minimise their impact on the EMG signal.

Cross-talk

Cross-talk is a concern when recording EMG data from the torso musculature due to overlapping and interweaving muscle fibres of adjacent muscles of the torso (Lindstrom & Magnusson, 1977). Appropriate electrode placement discussed in the previous section can help ensure that EMG data represents the activity of the muscle or group of muscles of interest, which can be used to interpret EMG data in the context of the initial purpose of measuring muscle activity (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Inter-electrode distance can also influence the possibility that muscle activity is recorded from adjacent or underlying muscles. An inter-electrode distance of 20mm has been recommended to maximise the amplitude of the action potential (Clancy et al., 2002; Hermens et al., 2000). No specific recommendations for the torso muscles were found regarding inter-electrode distance; however, 20 to 25mm was the most common inter-electrode distance used or recommended from the literature search (e.g. Kavcic et al. (2004); Kumar et al. (2003); McGill (1991); McGill et al. (1996)).

Heart rate and movement artefact

Due to the close proximity of the torso muscles to the heart and the conduction of electrical activity through the torso, EMG signals measured from the torso muscles are highly susceptible to contamination from electrical signals that cause the heart muscles to contract compared to EMG signals from the limb muscles (Drake & Callaghan, 2006; Redfern, Hughes, & Chaffin, 1993). The filtering of low frequencies from EMG signals can reduce the contamination of heart rate artefact on torso muscle EMG signals. Redfern et al. (1993) used a high-pass digital filter with different cut-off frequencies to determine an appropriate cut-off frequency to remove heart rate artefact from torso muscle EMG signals. Participants in their study performed isometric flexion and extension of the torso at exertion levels equivalent to 0, 10, 20, 40, and 100% of their maximum voluntary contraction (MVC) while EMG data were recorded from rectus abdominis, external oblique, and thoracic and lumbar erector spinae. Figure 2-7 is taken from the article by Redfern et al. (1993) and shows the effects of 0, 10, 30, and 60 Hz cut-off frequencies on integrated EMG amplitudes of thoracic erector spinae at the level of T9 while a participant performed torso extension at four different exertion levels. Heart rate artefact produced spikes in the 10, 20, and 40%MVC graphs when a cut-off frequency of 10 Hz or less was used; however, the effects of heart rate artefact on the thoracic erector spinae signals was significantly reduced when the cut-off frequency was 30 Hz or higher. The authors concluded that a high-pass digital filter with a cut-off frequency between 20 and 30 Hz was effective in removing heart rate artefact from torso muscle EMG signals. Later, Drake and Callaghan (2006) compared different techniques for removing heart muscle activity contamination from torso muscle EMG signals. They concluded that a digital Butterworth filter was the most appropriate high-pass filter for this purpose because of how quickly and easily this type of filter can be used.

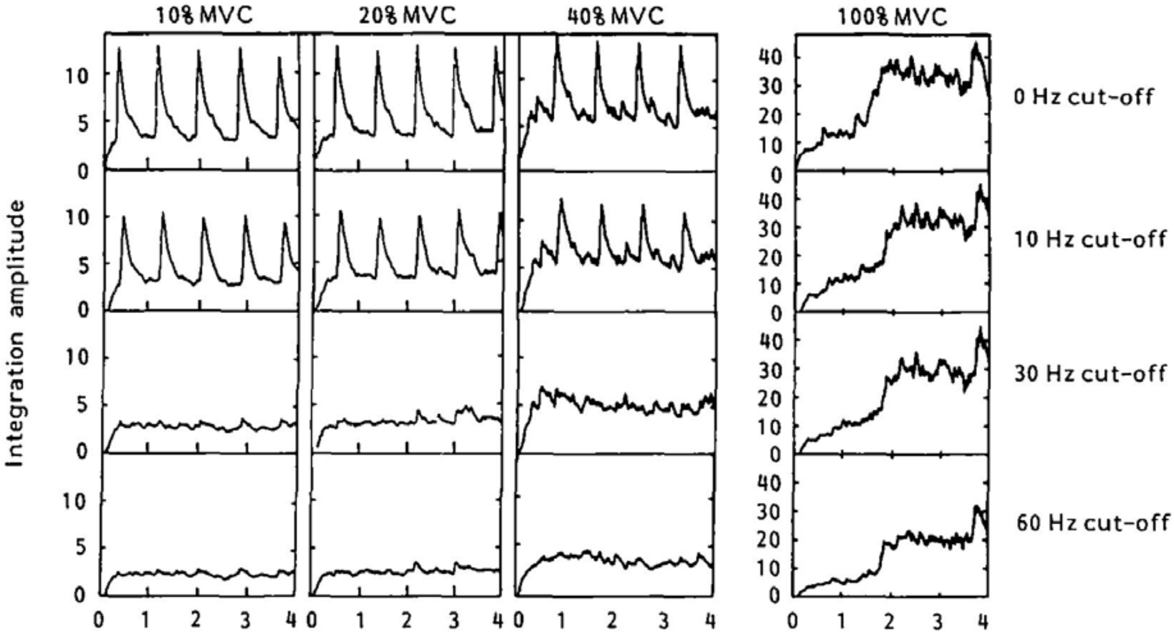

Figure 2-7. Figure from Redfern et al. (1993) displaying time series graphs of integrated EMG amplitudes (in µV) of thoracic erector spinae at the level of T9 for different exertion levels of isometric torso extension (percent of maximal voluntary contraction from left to right) using cut-off frequencies of 0, 10, 30, and 60 Hz (from top to bottom).

In addition to removing heart rate artefact, a high-pass filter with a 20 to 30 Hz cut-off would likely remove noise produced by sway from EMG cables. Movement artefact from cables can have high amplitude but tend to reside in frequencies below 20 Hz (Clancy et al., 2002; Winter, 2009). Thus, movement artefact and heart rate artefact can be removed from torso muscle EMG signals using a high-pass filter with a 20 to 30 Hz cut-off frequency. While some frequencies that could represent true muscle activity may be rejected when using such a high cut-off frequency (Redfern et al., 1993), a 20 to 30 Hz high-pass filter seems to be the most appropriate strategy to remove low frequency contamination of the signal.

Normalising the EMG Signal

EMG normalisation can control for many of the “Causative” factors listed in the schematic diagram created by De Luca (1997) in Figure 2-8 that can influence the signal recorded. It is difficult to draw meaningful comparisons of raw EMG signals between muscles, let alone between participants, without a reference value to which the signal can be compared. For example, the distribution of subcutaneous fat around the abdomen may be different from the fat distribution around the upper and lower back, resulting in different levels of impedance for muscles in these regions which would affect the EMG signal (Nordander et al., 2003). EMG signals should be normalised to a reference value to permit comparison of muscle activity between different muscles and participants due to intra- and inter-subject differences in factors that influence the EMG signal (Konrad, 2005; Lehman & McGill, 1999).

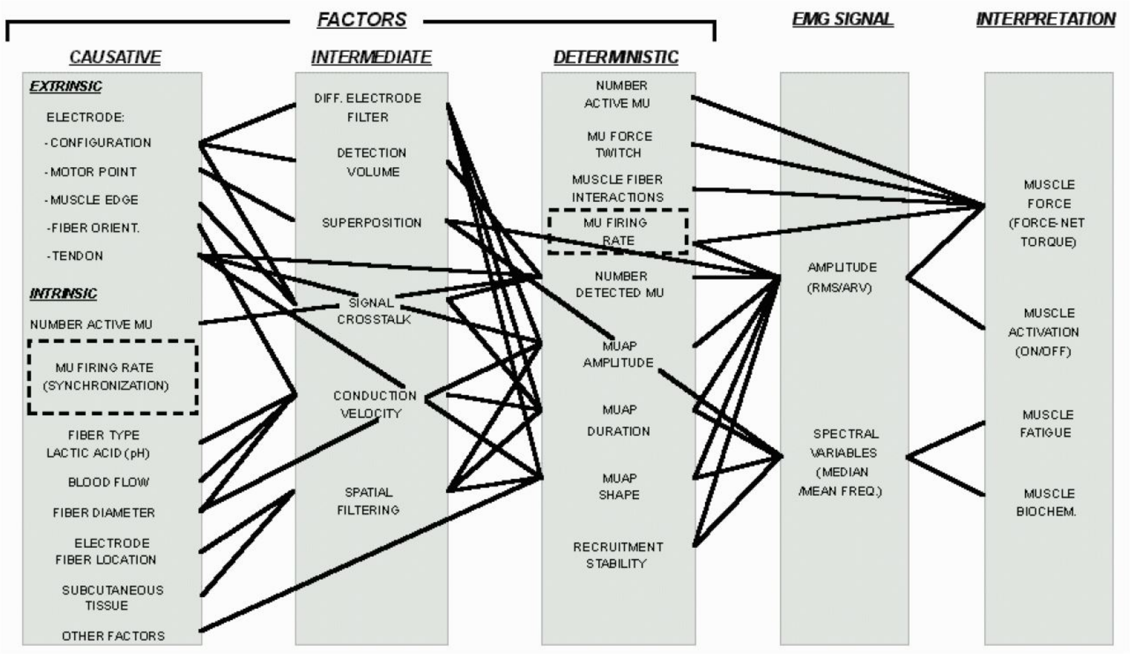

Figure 2-8. Schematic diagram from De Luca (1997) showing the factors that influence the EMG signal and, consequently, interpretation of EMG data. Normalisation of the EMG signal to a reference movement can help to control for the "Causative" factors listed in this figure.

A common strategy to normalise EMG signals is to use the highest EMG recording from MVC trials to represent 100% activity for each individual muscle (Burden, 2010; De Luca, 1997). An individual's ability to produce a true MVC, however, is dependent on many factors. For example, EMG signal amplitude during MVC trials can be influenced by an individual's motivation and their threshold for pain or discomfort when attempting to produce a maximal physical output (Caldwell et al., 1974; Kankaanpää, Taimela, Webber, Airaksinen,

& Hänninen, 1997; Komi & Buskirk, 1970). Verbal encouragement has been used as a strategy to boost motivation and elicit higher efforts during maximal physical tests (Bickers, 1993; Jung & Hallbeck, 2004) and may increase EMG signal amplitude during MVCs (Binboğa, Tok, Catikkas, Guven, & Dane, 2013). EMG signal amplitude during MVC can also be increased when an individual focuses their attention on the outcome of a movement as opposed to the movement itself. Marchant, Greig, and Scott (2009) observed higher EMG signal amplitudes in biceps brachii when participants were encouraged to focus on moving an object with elbow flexion (i.e. the outcome) than when focus was placed on performing elbow flexion alone (i.e. the movement). Verbal encouragement and instructing participants to focus on an outcome of movements used in MVCs may produce neural activity to the muscle that most closely resembles a true maximal effort.

Normalisation can also be accomplished using a maximum or a mean value during a dynamic movement, for example from a trial during testing (Konrad, 2005). This method has an advantage over using a value from MVC trials because the reliance on an individual's ability to produce a true maximal effort is removed. The disadvantage of using a dynamic trial to normalise EMG signals is that direct comparisons between EMG data from different muscles cannot be made. Additionally, it is difficult to relate EMG data measured during different activities, such as front crawl swimming and dry-land strength training exercises, when EMG data are normalised to different movements. Data produced by different normalisation techniques could be compared during post-processing to determine which technique is most reliable within participants; however, the selection of normalisation technique should be determined by the purpose of the investigation.

Challenges of EMG Underwater

Waterproofing

Waterproofing of EMG apparatus helps to protect participants from electrical shock, avoid equipment damage, and reduce contamination of the myoelectric signal (Kaneda, Ohgi, Mckean, & Burkett, 2013). Appropriate waterproofing strategies have been shown to produce similar EMG signals and preserve the EMG frequency spectrum underwater and on land (Martens, Janssens, Staes, Dingenen, & Daly, 2014; Pinto et al., 2010; Rainoldi, Cescon, Bottin, Casale, & Caruso, 2004). In early studies of muscle activity in swimming, adhesive plaster and vinyl chloride paint were used to seal EMG electrodes (Ikai et al., 1964). Medical-grade waterproof adhesive bandages (e.g. Opsite Flexfix, TAPE SILVER - 3M®) are now often used to cover the electrodes (da Silva Carvalho et al., 2010; Karla de Jesus et al., 2011; Figueiredo, Sanders, et al., 2013) and some researchers have used extra tape (e.g. sports tape) to help seal the edges of the waterproof bandages (Martens et al., 2016; Oliveira & Sanders, 2017). Kaneda et al. (2013) recommended using putty to fill the gap produced by the EMG leads between the adhesive bandage and the skin. One company has developed proprietary circular rubber gaskets with a hole in the middle (WEL-SUB; Cometa, Italy; 15mm total diameter, 4mm hole diameter, 0.5 to 1mm thickness) that can be adhered around the Ag-AgCl nipple of an electrode. The EMG lead can then be connected to the electrode per usual. The surface of the rubber gaskets is adhesive to help maintain a water-tight connection with the electrode and the EMG lead. The company has claimed to have success in waterproofing the EMG electrode and lead complex without the need for adhesive bandages (personal communication July 2018; Cometa Srl (5 Sep 2018)).

Waterproof bandages are easily accessible from medical supply companies. Further, adhesive bandages can be quickly removed from a participant and discarded while plaster, paint, and putty may be more difficult to clean away from the skin after data collection. The proprietary rubber gaskets (Cometa, Italy) may present a simpler option than waterproof adhesive in that less material is needed during EMG preparation; however, the EMG signal acquired with and without the gaskets should be tested by a third party to ensure that the gasket itself does not change the EMG signal. The use of adhesive bandages is therefore likely to be the most practicable strategy for waterproofing EMG equipment.

Skin preparation requires special considerations. While conductive gel or paste can help decrease signal impedance (Clancy et al., 2002), the adhesion between the skin and waterproofing tape may be compromised by conductive material that is often water-soluble, potentially leading to a loss of muscle signal. Therefore, it may be beneficial to avoid the use of water-soluble conductive gel and to shave and cleanse with alcohol the area surrounding the electrode site to help ensure waterproofing of the EMG equipment.

Some researchers have used whole-body swimsuits, such as the Speedo FASTSKIN^{TM}, to reduce the impact of mechanical artefact from water flow over the electrodes. A custom hole is made in the FASTSKIN^{TM} swimsuit to allow the EMG cables to exit the suit while minimising effects on the participant’s swimming technique (Karla de Jesus et al., 2011; Figueiredo, Rouard, Vilas-Boas, & Fernandes, 2013; Vitor et al., 2016). This innovative strategy to minimise noise should be implemented for swimming research.

Wired vs. Wireless

Wired transmission and telemetry have been used to record EMG since early studies of muscle activity in swimming (Ikai et al., 1964; Maes et al., 1975; Piette & Clarys, 1979). Over the past 10 years of underwater biomechanics research, wired (Karla de Jesus et al., 2011; Figueiredo, Rouard, et al., 2013; Figueiredo, Sanders, et al., 2013; Oliveira et al., 2010) and wireless (Martens et al., 2016; Martens, Daly, et al., 2015; Martens et al., 2014; Oliveira & Sanders, 2017) EMG technology continue to be used; however, both strategies have unique advantages and disadvantages. An obvious benefit of wireless over wired EMG is the elimination of cables that can interfere with normal swimming technique, though other issues arise when the direct connection between the EMG electrodes and the data collection computer is removed. Myoelectric signals can be continuously transmitted to a data collection computer with wired EMG even when the electrodes are submerged. Wireless EMG equipment uses radio waves, Bluetooth, or wifi to send EMG signals to a data collection computer and none of these signals can be transmitted across media (e.g. water to air and *vice versa*); therefore, wireless EMG cannot provide a continuous stream of data to a computer located on land when the EMG sensors are submerged. To circumvent this barrier in some of the first studies that used telemetry (Clarys et al., 1983; Piette & Clarys, 1979), an antenna from the EMG equipment attached to the swimmer exited the water to permit on-line transmission of the signal to the data collection computer. Modern wireless EMG devices are equipped with an onboard memory (typically between 7 minutes (KINE Ltd., Iceland) and 30 minutes (Cometa, Italy) of data sampled at 1600 Hz) to store EMG when the sensors are submerged and the ability to directly transmit the signal is lost. Data can be transmitted when the sensors emerge from the water and the connection is re-established.

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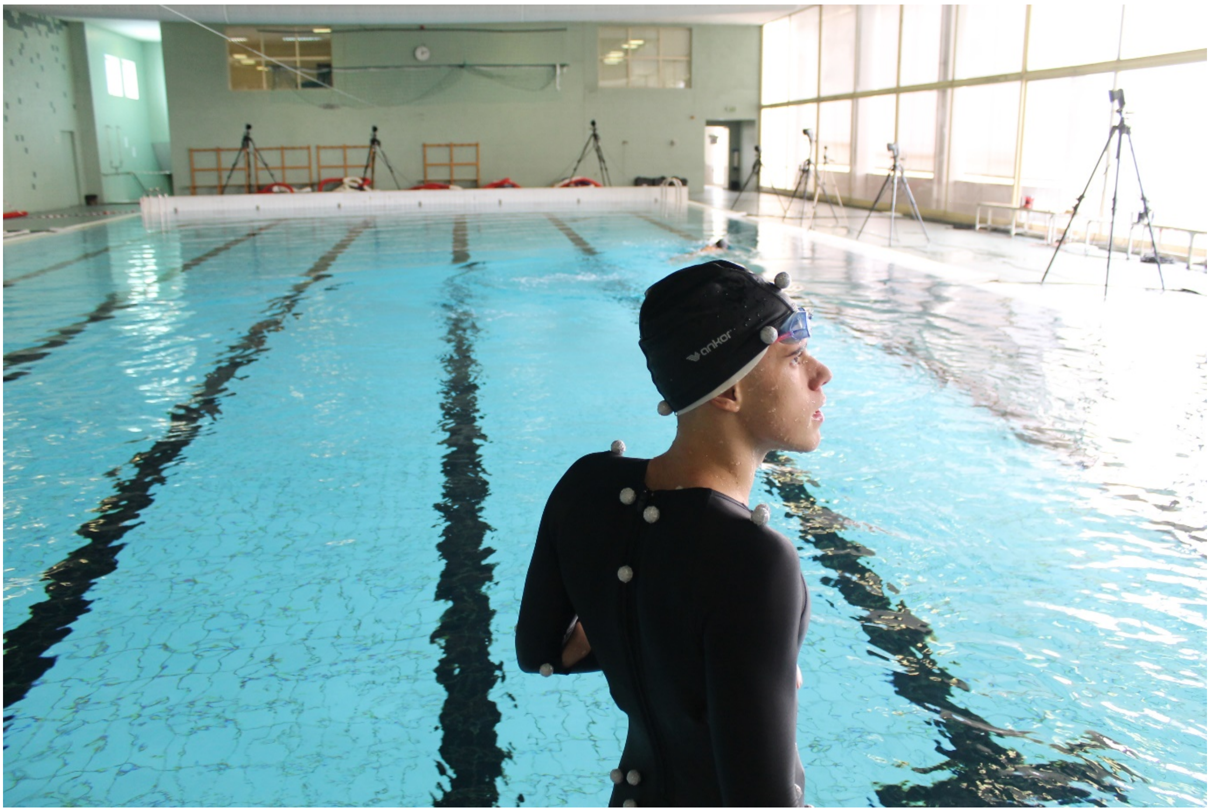
CHAPTER 3:

Kinematic differences in shoulder roll and hip roll at different front crawl speeds



Foreword

The study reported in this chapter was designed to determine whether there are differences in the range and rate of rotation between the upper and lower torso, that is ‘torso twist’, in front crawl at sprint and middle-distance pace. The findings of this investigation could then be used to develop hypotheses relating to the relationships between torso muscle activity and rotational kinematics about the body’s longitudinal axis at different swimming speeds.

The following study was accepted for publication by the *Journal of Strength & Conditioning Research* as of 30th May 2019. The version of the manuscript that appears in this chapter includes revisions to the article accepted by the *Journal of Strength & Conditioning Research* recommended by the examiners of this thesis.

> **Andersen J**, Sinclair P, McCabe C, Sanders R (2019, ahead of print). Kinematic differences in shoulder roll and hip roll at different front crawl speeds. *Journal of Strength & Conditioning Research*.

Abstract

Dry-land strength training is a common component of swimming programs; however, its efficacy is contentious. A common criticism of dry-land strength training for swimming is a lack of specificity. An understanding of movement patterns in swimming can enable dry-land strength training programs to be developed to elicit adaptations that transfer to improvements in swimming performance. This study aimed to quantify the range and velocity of hip roll, shoulder roll, and torso twist (produced by differences in the relative angle between shoulder roll and hip roll) in front crawl at different swimming speeds. Longitudinal torso kinematics were compared between sprint and 400m pace front crawl using 3D kinematics of thirteen elite Scottish front crawl specialists. The range (sprint: 78.1°; 400m: 61.3°) and velocity of torso twist (sprint: 166.3°/s; 400m: 96.9°/s) were greater at sprint than 400m pace. These differences were attributed to reductions in hip roll (sprint: 36.8°; 400m: 49.9°) without corresponding reductions in shoulder roll (sprint: 97.7°; 400m: 101.6°) when participants swam faster. Shoulder roll velocity (sprint: 190.9°/s; 400m: 139.2°/s) and hip roll velocity (sprint: 75.5°/s; 400m: 69.1°/s) were greater at sprint than 400m pace due to a higher stroke frequency at sprint pace (sprint: 0.95 strokes/s; 400m: 0.70 strokes/s). These findings imply that torques acting to rotate the upper torso and the lower torso are greater at sprint than 400m pace. Dry-land strength training specificity can be improved by designing exercises that challenge the torso muscles to reproduce the torques required to generate the longitudinal kinematics in front crawl.

Keywords: torso twist, biomechanics, sprint, middle-distance, performance

Introduction

To maximise the probability that strength training adaptations will transfer to improvements in performance, training must be based on the demands of a sport (González-Badillo & Sánchez-Medina, 2010; Izquierdo et al., 2002). The lack of effectiveness of many dry-land strength training programs in improving swimming performance is often attributed to a lack of specificity in training (Girold, Maurin, Dugue, Chatard, & Millet, 2007; Tanaka, Costill, Thomas, Fink, & Widrick, 1993; Tanaka & Swensen, 1998). Transference of strength training gains to performance can be enhanced by designing exercises that match the demands associated with the movement patterns used within a sport (Young, 2006). Dry-land strength training specificity for swimming can therefore be improved with a better understanding of the movement patterns used in swimming.

Longitudinal body rotation is essential for maximising performance in front crawl swimming (Counsilman & Counsilman, 1994; Maglischo, 2003). Rotation of the shoulders and hips about the body's longitudinal axis, known respectively as shoulder roll and hip roll, depend on swimming speed (Psycharakis & Sanders, 2010). Some characteristics of shoulder roll and hip roll remain consistent across different front crawl speeds; for example, the shoulders roll through a greater range of motion than the hips regardless of swimming speed (Cappaert et al., 1995; Yanai, 2003). The effect of swimming speed on several features of longitudinal rotation in front crawl, however, remain unclear. For example, it is unknown how torso twist produced by differences in the relative angles of hip roll and shoulder roll varies with swimming speed. Further, the influence of swimming speed on the rate of change (or velocity) of hip roll, shoulder roll, and torso twist has never been reported. Considering the association between torso muscle activity and the magnitude and speed of twisting motions of the spine (Kumar et al., 1996; Marras & Granata, 1995), differences in the range and velocity of torso twist in front crawl may influence the demands on the torso muscles. Our understanding of the torso muscle requirements in front crawl may therefore be limited by the lack of evidence of torso twist characteristics in front crawl swimming.

Total hip roll, a measurement of the range of hip roll from one side to the other, tends to decrease as swimming speed increases while total shoulder roll, which is the range of shoulder roll from one side to the other, does not seem to change with increasing speed as much as total hip roll. McCabe and Sanders (2012) reported a total hip roll of 57 degrees at 1.50 m/s during a 400m maximal effort while Psycharakis and Sanders (2008) reported a total hip roll of 44 degrees at 1.68 m/s in the first 50m of a 200m maximal front crawl test. Psycharakis and McCabe (2011) reported an even lower total hip roll of 39 degrees at 1.81 m/s during a maximal 25m sprint. Despite the 18 degrees difference in total hip roll between 400m pace and sprint front crawl swimming, total shoulder roll remained between 105 and 111 degrees across all three studies. Differences in the range and/or timing of hip roll and shoulder roll require twist within the torso. Data from the studies by McCabe and Sanders (2012), Psycharakis and Sanders (2008), and Psycharakis and McCabe (2011) indicate that the range of torso twist is likely to increase with swimming speed; however, differences in torso twist from the same group of swimmers swimming at different front crawl speeds have never been examined.

The time for the hips and shoulders to roll from one side to the other and back again is determined by the duration of the arm stroke cycle (Sanders & Psycharakis, 2009; Yanai, 2001b). The velocities of hip roll and shoulder roll are therefore influenced by the range of hip roll and shoulder roll, respectively, and the number of stroke cycles per unit of time, or stroke frequency. It is well documented that stroke frequency increases as swimming speed increases (Chollet et al., 2000; Craig et al., 1985; Schnitzler et al., 2008; Seifert et al., 2004);

however, the influence of swimming speed on hip roll velocity and shoulder roll velocity is unknown. Changes in the relative angle between hip roll and shoulder roll and differences in stroke frequency across front crawl speeds suggest that torso twist velocity may also change with swimming speed, but torso twist velocity has yet to be quantified in the scientific literature.

Although twist of the shoulders and hips relative to each other is influenced by the torques produced by the actions of the upper and lower limbs, it may be hypothesised that the differences between shoulder and hip rotation, manifest in changing torso twist angles, is also influenced by the actions of the torso muscles connecting the shoulders and hips. Therefore, it is likely that differences in torso twist rates of change, that is, torso twist velocities, may reflect differences in demands on the torso muscles to control posture and maintain stability of the swimmer’s torso. Further, if there are differences in the relative magnitudes and velocities of shoulder and hip roll between paces, demands on the torso muscles are likely to differ between swimming speeds. Therefore, insights into these demands may be gained by quantifying the differences in the range and velocity of torso twist at different swimming paces.

While the ranges of hip roll and shoulder roll at different swimming speeds have been examined in separate studies, the differences in the velocities of hip roll and shoulder roll between swimming speeds have never been reported. Moreover, the range and velocity of torso twist produced by differences in hip and shoulder roll at different front crawl speeds have never been examined to our knowledge. These gaps in swimming research present a barrier to understanding the movement patterns in front crawl swimming that can be used to improve the specificity of dry-land strength training for swimmers. Therefore, the purpose of this study was to quantify the range and velocity of hip roll, shoulder roll, and torso twist in front crawl at different swimming speeds. The differences in the longitudinal kinematics between speeds will further our understanding of the movement patterns in front crawl swimming which can be used to develop insight into the demands on the torso muscles in front crawl swimming.

Methods

Experimental approach to the problem

This cross-sectional study of three-dimensional kinematics enabled analysis of the movement patterns of high-level front crawl swimming for two different event distances (i.e. 50m and 400m freestyle). National and international level swimmers were recruited because of their ability to produce movement patterns that can provide insights into the requirements for high level swimming performance. While experienced swimmers are known to reliably produce consistent swimming technique (Chatard, Collomp, Maglischo, & Maglischo, 1990), multiple trials at both swimming paces were collected to account for individual variability inherent of human movement.

Participants

Three-dimensional coordinate data of a 15 segment whole-body model of thirteen national and international level male Scottish front crawl specialists (age: 17.54 ± 1.98 years, range 15 to 22 years; height: 181.18 ± 4.98 cm; body mass: 71.58 ± 6.26 kg) were analysed from a data set that was previously utilised in the studies of McCabe et al. (2011) and McCabe and Sanders (2012). Participants had specialised in front crawl for a minimum of two years, were not currently injured or recovering from injury, and held a short course personal best time of either less than 24.60s for 50m or less than 4min10s for 400m. The protocols and procedures were approved by the university ethics committee. All participants were informed of the risks and benefits of the study and provided written consent prior to data collection. For participants under the age of 18, participants and a parent or guardian provided written consent.

Procedures

The data collection by McCabe was conducted in an indoor 25m pool. Participants were marked to enable identification of the following anatomical landmarks: the vertex of the head (on top of the swim cap), the left and right: tip of the 3rd distal phalanx of the finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, lateral aspect of the 5th metatarsophalangeal joint, and tip of 1st phalanx of the foot (big toe). After an individualised warm up, participants swam 4x25m at sprint pace and one 400m effort at a pace that would result in the fastest time possible. After each sprint trial, participants swam back to the start position at recovery pace and rested in-water for two minutes before beginning the next trial. The order of swimming pace was randomised and participants swam for at least five minutes to recover after completing the first pace, then exited the pool for an additional ten minute rest before warming up again and completing the second pace.

As participants swam through a calibration volume (4.5m long, 1.0m wide, and 1.5 in height) located 15.25m from the starting wall, their motion was captured by six JVC KY32 CCD cameras (four below and two above the water surface) at a frame rate of 50 Hz with a shutter speed of 1/120 seconds. Each camera contained a high quality lens and resolution for each camera was optimised to produce the clearest image possible. The gain on each camera was also adjusted to maximise image quality. Each trial began from a push start and participants were required to not breathe as they swam through the calibration volume to avoid any effect of the breathing actions on their swimming technique (Psycharakis & McCabe, 2011; Seifert et al., 2004). Swimmers familiarised themselves with the breath-holding requirement during warm up. All participants used a six-beat flutter kick at both swimming paces.

Data processing

One stroke cycle (SC) was defined as the moment the tip of the third digit of one hand entered the water to the subsequent entry of that digit on the same hand performed completely within the calibrated space. At sprint pace, one SC was analysed for each of the four 25m trials. During the 400m effort, one SC was recorded from the first 25m length of each 50m lap. SCs from laps 2, 3, 4 and 5 during the 400m effort were analysed, totalling four observations per swimmer at 400m pace. These laps were selected to align with previous findings that laps 1, 7, and 8 were consistently different from laps 2-6 (McCabe & Sanders, 2012). Lap 6 was excluded to further minimise the effect of fatigue on swimming technique. Due to marker occlusion during data collection that prevented digitization of landmarks over several consecutive frames, one trial from one participant at 400m pace (P4) was discarded. Data were retained for all four trials at both paces from every other participant.

Three-dimensional reconstruction from manual digitization of the anatomical landmarks was conducted using the Ariel Performance Analysis System (direct linear transformation algorithms from Abdel-Aziz and Karara (1971)). Errors due to digitization for the variables used in the current study were considered small from digitization reliability tested in a previous study (McCabe et al., 2011). To prevent data loss during filtering, an additional 30 frames were extrapolated by reflection. Fourier truncation was used to filter the position data of the body landmarks. This filtering strategy was deemed appropriate because the cyclic nature of movements in front crawl swimming results in periodic data (Bartlett, 2007). Residual analysis indicated that a 6 Hz cut-off was suitable to smooth the data. SC length was then standardised to 201 points using a Fourier transform and inverse transform so that each datum represented a half percentage of the SC (i.e. 0-100%).

The filtered anatomical landmark data were entered into a bespoke MATLAB (Mathworks, Inc.) analysis program written by the last author. The orthogonal external reference system was defined by the horizontal X-axis pointing in the swimming direction, the Y-axis pointing vertically up, and the horizontal Z-axis pointing to the swimmer's right. Shoulder roll and hip roll were calculated independently for each percentile of the SC as the angle, expressed in degrees, between the Z-axis and vectors connecting the shoulders and hips, respectively, projected onto the YZ plane.

Data analysis

Average swimming velocity, calculated by dividing the horizontal component of the centre of mass displacement (determined by McCabe using the 'eZone method' (Deffeyes & Sanders, 2005)) by SC time, was 1.81 ± 0.06 m/s at sprint pace and 1.47 ± 0.06 m/s at 400m pace.

Stroke frequency was determined using the inverse of the time to complete one SC (stroke/s). Torso twist was the difference in the relative angles of shoulder roll and hip roll, similar to the expression of 'trunk twist' described by Yanai (2001b, 2003) and Psycharakis and Sanders (2008). Torso twist was calculated for each percentile of the SC in degrees. Hip roll velocity, shoulder roll velocity, and torso twist velocity were the rate of change of hip roll, shoulder roll, and torso twist, respectively, and were expressed as angular velocities (in degrees per second) using the time derivatives of hip roll, shoulder roll, and torso twist with the central difference method.

Range of hip roll, range of shoulder roll, and range of torso twist were determined separately for each trial by summing the maximum magnitude of hip roll, shoulder roll, and torso twist, respectively, to the left side and to the right side. Averages for hip roll velocity, shoulder roll velocity, and torso twist velocity were calculated using the mean of the absolute values of hip roll velocity, shoulder roll velocity, and torso twist velocity, respectively, over each entire SC.

Statistical analysis

Statistical tests were performed using IBM SPSS Statistics 24 ($\alpha = 0.05$), with the exception of effect sizes which were calculated manually (Fritz, Morris, & Richler, 2012). Intra-class correlations between swimming trials were determined using a single-rating, absolute agreement, two-way mixed random effects model analysis (Koo & Li, 2016) for stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity at sprint pace and 400m pace.

Means and 95% confidence intervals (i.e. the t-value for the sample size ($n = 13$) multiplied by the standard error of the sample mean) were calculated at both swimming paces for stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity. Confidence intervals improved our ability to compare and interpret differences between swimming paces by providing a range about the mean of each kinematic variable in which the true mean was likely to fall for either pace. The Shapiro-Wilk test indicated that all variables were normally distributed. Separate paired t-tests were conducted to evaluate the differences in stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity between sprint pace and 400m pace. Effect sizes were determined using Cohen’s d and interpreted with the following recommendations: small 0.2, moderate 0.5, and large 0.8 (J. Cohen, 1988). *Post* *hoc* power analysis was conducted using open-source software (G*Power 3.1) (Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Intra-class correlations were high for stroke frequency (sprint pace: 0.93; 400m pace: 0.98) range of hip roll (sprint pace: 0.90; 400m pace: 0.93), range of shoulder roll (sprint pace: 0.85; 400m pace: 0.94), range of torso twist (sprint pace: 0.82; 400m pace: 0.91), average hip roll velocity (sprint pace: 0.90; 400m pace: 0.91), average shoulder roll velocity (sprint pace: 0.83; 400m pace: 0.96), and average torso twist velocity (sprint pace: 0.84; 400m pace: 0.89) at both paces. High intra-class correlations of these variables indicate torso rotation patterns were similar across participants.

Time series for ensemble averages for all participants of hip roll, shoulder roll, and torso twist are shown in Figure 3-1 and time series for ensemble averages of hip roll velocity, shoulder roll velocity, torso twist velocity are shown in Figure 3-2 for one SC at sprint and 400m pace.

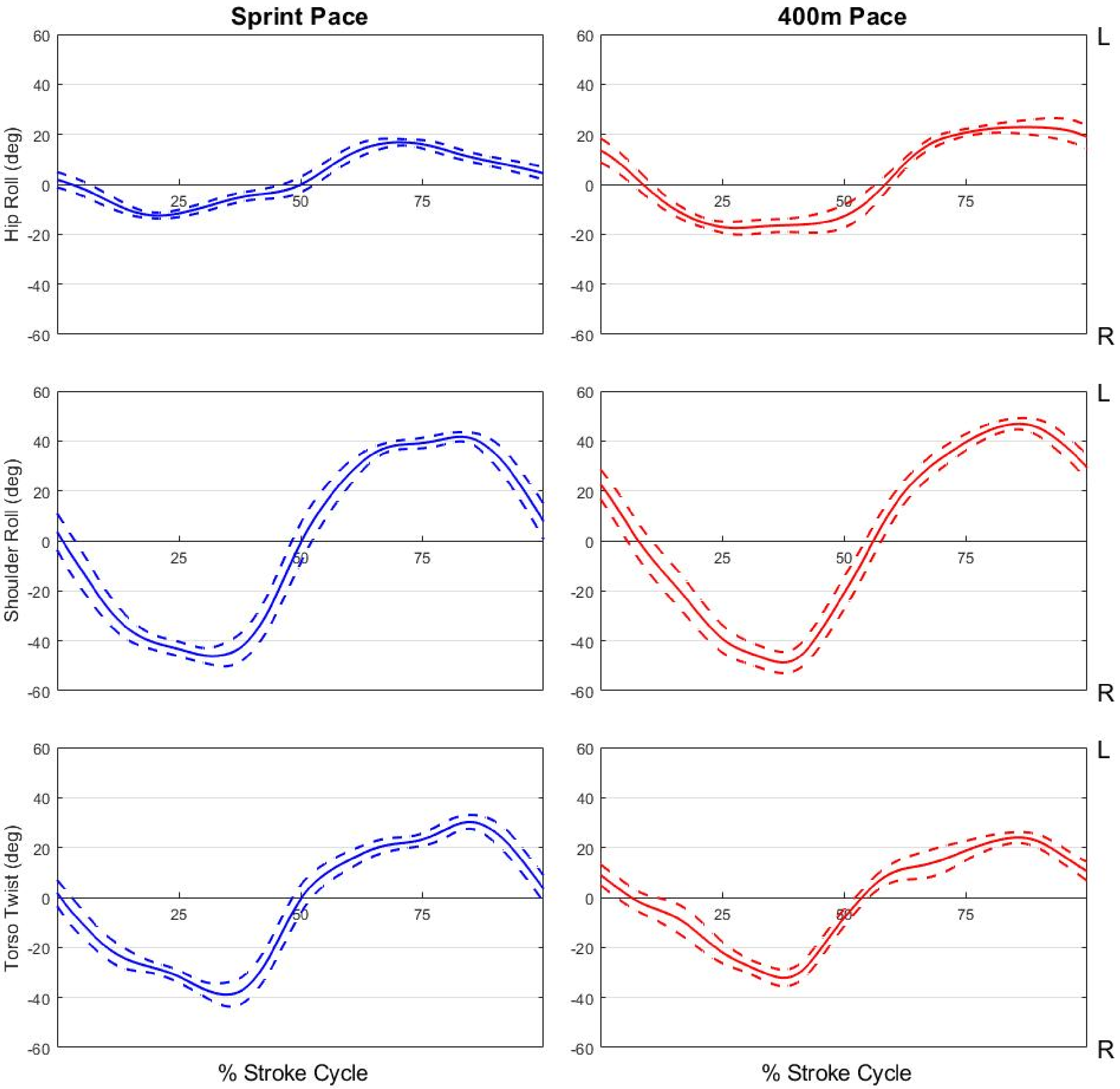


Figure 3-1. **Time series with ensemble averages for hip roll, shoulder roll, and torso twist at sprint pace and 400m pace. Dashed lines represent 95% confidence intervals calculated using the *t*-value and standard error of the sample mean. Positive values indicate rotation to the swimmer's left (i.e. in the anticlockwise direction when viewing the swimmer from behind) and negative values indicate rotation to the swimmer's right (i.e. in the clockwise direction when viewing the swimmer from behind). Swimmers began these SCs with the right hand. Time series for SCs beginning with the left hand were similar to this figure.**

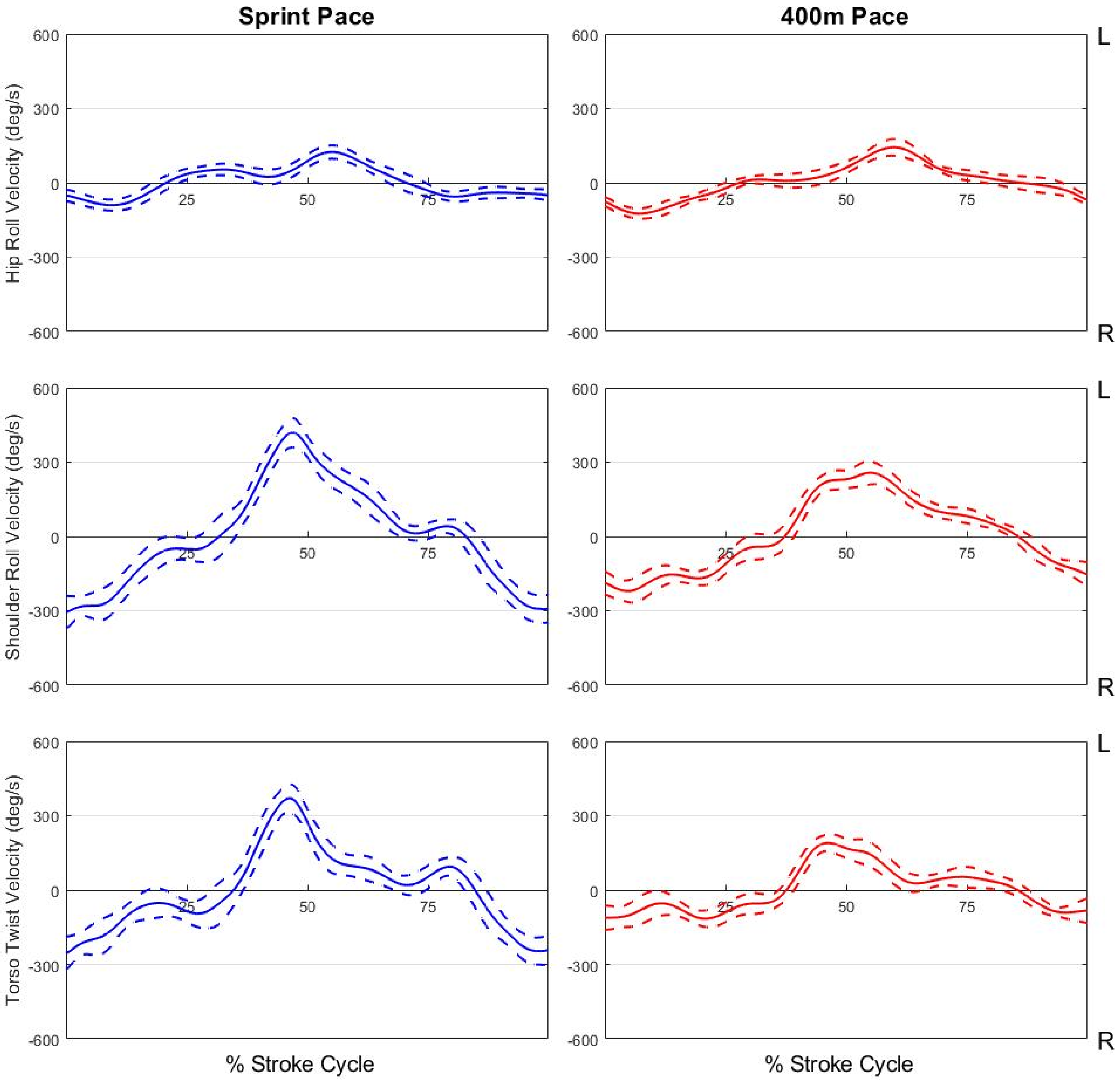


Figure 3-2. Time series with ensemble averages for hip roll velocity, shoulder roll velocity, and torso twist velocity at sprint pace and 400m pace. Dashed lines represent 95% confidence intervals calculated using the *t*-value and standard error of the sample mean. Positive values indicate rotation to the swimmer's left (i.e. in the anticlockwise direction when viewing the swimmer from behind) and negative values indicate rotation to the swimmer's right (i.e. in the clockwise direction when viewing the swimmer from behind). Swimmers began these SCs with the right hand. Time series for SCs beginning with the left hand were similar to this figure.

Table 3-1 shows means, 95% confidence intervals of the true mean using the *t*-distribution of the sample mean, effect sizes, and statistical power for comparisons between paces of stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity. Stroke frequency was greater at sprint pace than at 400m pace ($t(12) = 12.27$, $p < 0.01$) with a large effect size. Range of hip roll was greater at 400m pace than at sprint pace ($t(12) = 6.77$, $p < 0.01$) with a large effect size while range of shoulder roll was similar between paces ($p = 0.14$). Range of torso twist ($t(12) = 6.88$, $p < 0.01$), average shoulder roll velocity ($t(12) = 9.17$, $p < 0.01$), and average torso twist velocity ($t(12) = 12.30$, $p < 0.01$) were greater at sprint pace than at 400m pace with large effect sizes. Average hip roll velocity was also greater at sprint pace than at 400m pace ($t(12) = 2.98$, $p < 0.05$) but with a moderate effect size.

Table 3-1. Stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average absolute hip roll velocity, average absolute shoulder roll velocity, and average absolute torso twist velocity at sprint pace and 400m pace.

	Sprint Pace		400m Pace		Effect Size (Cohen's *d*)	Power (*n* = 13)
	Mean	95% CI	Mean	95% CI		
Stroke Frequency (stroke/s)	0.95**	0.04	0.70	0.04	3.73	1.0
Range of Hip Roll (°)	36.8**	*3.1*	49.9	*5.6*	-1.58	1.0
Range of Shoulder Roll (°)	97.7	*3.1*	101.6	*5.9*	-0.46	0.40
Range of Torso Twist (°)	78.1**	*3.4*	61.3	*4.7*	2.23	1.0
Average Absolute Hip Roll Velocity (°/s)	75.5*	7.1	69.1	7.9	0.52	0.66
Average Absolute Shoulder Roll Velocity (°/s)	190.7**	9.9	139.2	11.5	2.92	1.0
Average Absolute Torso Twist Velocity (°/s)	166.3**	*10.0*	96.9	*8.2*	4.13	1.0

Significantly different from 400m pace (*$p < 0.05$, **$p < 0.01$).

Discussion

The purpose of this study was to quantify the range and velocity of hip roll, shoulder roll, and torso twist in front crawl at different swimming speeds. The differences in hip roll and shoulder roll that contributed to the changes in the range and velocity of torso twist between paces will further understanding of the demands on the torso muscles in front crawl swimming. The findings from this study contribute to the knowledge of movement patterns in front crawl that can be used to improve the specificity of dry-land strength training for swimmers.

The larger range of torso twist at sprint pace than at 400m pace seemed to be the result of a reduction in hip roll without a corresponding reduction in shoulder roll when participants were swimming faster. The range of hip roll and range of shoulder roll observed in the current study are consistent with trends of total hip roll and total shoulder roll across different swimming speeds from previous findings (Psycharakis & Sanders, 2008). The similar range of shoulder roll between paces and the higher stroke frequency at sprint pace than at 400m pace meant the swimmers rolled their shoulders faster as swimming speed increased. This was reflected in an average shoulder roll velocity that was 37% greater at sprint pace than at 400m pace (Table 3-1). Despite the smaller range of hip roll at sprint pace than at 400m pace, the higher stroke frequency resulted in an increase in hip roll velocity as swimming speed increased; however, average hip roll velocity was only 9% greater at sprint pace than at 400m pace. Moreover, the effect size of the difference in average hip roll velocity was moderate while all other statistically significant differences between paces had large effect sizes (Table 3-1). The difference in torso twist velocity between swimming paces therefore seemed to be the result of the swimmers' ability to maintain their range of shoulder roll, despite an increase in stroke frequency, and to reduce their range of hip roll as they increased swimming speed.

The patterns of hip roll, shoulder roll, and torso twist in Figure 3-1 suggest the magnitude of rotation between the upper and lower torso was greater at sprint pace than at 400m pace. Furthermore, the difference in torso twist velocity between swimming paces implies the swimmers in this study rotated their upper torso with respect to their lower torso more rapidly at sprint pace than at 400m pace. The increase in torso twist velocity as swimming speed increased could have been from internal torques from muscle forces, external torques generated by the arm stroke and flutter kick, or both internal and external forces. Whether internal or external torques produced the increase in torso twist velocity as swimming speed increased, torso muscle activity is likely to increase with swimming speed since increases in the magnitude and speed of rotation between the upper and lower torso are associated with higher torso muscle activity (Marras et al., 1998; Marras & Granata, 1995). These findings suggest that the demands on the torso muscles are likely to be higher at faster swimming speeds but this cannot be stated with confidence without further research measuring the muscle activity at different paces.

Torques that produce rotation of the upper torso must have been higher at sprint pace than at 400m pace to achieve a similar range of shoulder roll at both paces considering the increase in stroke frequency as swimming speed increased. Hydrodynamic and buoyancy torques associated with the arm stroke produce longitudinal body rotation (Payton, Bartlett, Baltzopoulos, & Coombs, 1999; Yanai, 2001b, 2004) and could have contributed to the differences in shoulder roll velocity observed in the current study. Though the shoulders and hips roll somewhat independently in front crawl (Sanders & Psycharakis, 2009), longitudinal rotation is likely transferred from the shoulders to the hips. For example, angular momentum can be transferred along the torso during twisting motions of the spine through passive mechanisms (e.g. via connective tissue and intervertebral discs) (Kumar et al., 2003; Kumar et al., 1996) or with the assistance of muscle torques (Marras & Granata, 1995; Pink, Perry,

& Jobe, 1993; Shaffer, Jobe, Pink, & Perry, 1993). Greater torque acting to rotate the lower torso, separate from the torques acting to rotate the upper torso, may have therefore been required to reduce the range of hip roll as swimming speed increased. Sanders and Psycharakis (2009), for instance, hypothesised that hip roll is “dampened” compared to shoulder roll from torques associated with the flutter kick. Considering swimmers tend to increase kicking frequency as swimming speed increases (Chollet et al., 2000; Kelly de Jesus et al., 2016; Millet, Chollet, Chalies, & Chatard, 2002), internal torques (from muscle and joint reaction forces) and external torques (from fluid forces) produced by the flutter kick that act on the lower torso may have been greater at sprint pace than at 400m pace, which could have contributed to the reduction in hip roll as swimming speed increased. The differences in the longitudinal kinematics presented here indicate that the torques acting to rotate the upper torso and the torques acting to rotate the lower torso may be greater at sprint pace than at 400m pace. This may also indicate that the demands on the torso muscles increase as swimming speed increases. Quantification of the torques acting on the upper torso and lower torso in front crawl is required to test this hypothesis.

Practical Applications

This is the first study to investigate the velocity of hip roll, shoulder roll, and torso twist in front crawl swimming. Coaches can use these findings to guide recommendations for changes to swimming technique between sprint and middle-distance swimming. For example, swimmers can be encouraged to maintain their range of shoulder roll as stroke frequency increases with swimming speed. From the differences in the range and velocity of torso twist between swimming paces, torques acting to produce rotation of the upper torso and the lower torso, whether they are internal torques (e.g. muscle forces) or external torques (e.g. from the arm stroke and flutter kick), are likely to increase as swimming speed increases. Dry-land strength training specificity may be improved by designing exercises that challenge the torso muscles to generate torques that produce or resist longitudinal rotation of the upper torso and the lower torso. While the roles of the torso muscles in producing torso twist cannot be determined from the findings of this study, the differences in the torso kinematics can improve our understanding of the demands placed on the torso muscles in front crawl swimming. Swimmers are likely to benefit from dry-land training that conditions the torso muscles to produce torques that are associated with the torso twist velocities observed in this study, regardless whether those torques are generated from internal or external sources in front crawl swimming. Coaches are encouraged to consider the differences in the demands placed on swimmers competing over different distances when designing dry-land strength training, such as increase in torque required from the torso muscles. This could increase the likelihood that benefits from dry-land strength training will transfer to improvements in swimming performance.

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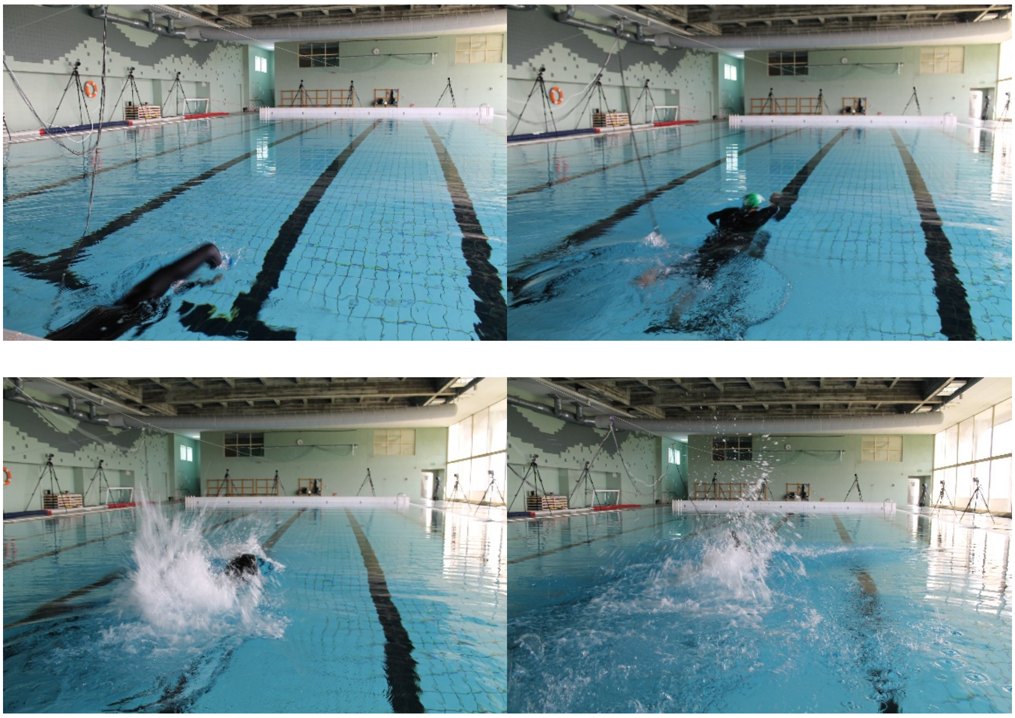
CHAPTER 4:

The application of Fourier analysis to demonstrate the impact of the flutter kick on longitudinal rotation in front crawl



Foreword

The following investigation was conducted to explore the influence of lower limb movements in front crawl swimming on body rotation about the longitudinal axis. The reduction in hip roll range as swimming speed increased, as described in Chapter 3, may have been the result of torques from the flutter kick. Torques acting on the pelvis could influence the requirements of the torso muscles. Therefore, the rotation about the body's longitudinal axis that is associated with the flutter kick and the influence of this rotation on the upper limbs were investigated.

The study in chapter was accepted for an oral presentation submitted to the 36th International Conference on Biomechanics in Sports in Auckland, New Zealand, 10-14 September 2018 (Appendix G):

> **Andersen J**, Sinclair P, McCabe C, Sanders R (2018). The application of Fourier analysis to demonstrate the impact of the flutter kick on longitudinal rotation in front crawl. *ISBS Proceedings Archive, 36*(1), Article 223. Available at: https://commons.nmu.edu/isbs/vol36/iss1/223.

Abstract

The contribution of the flutter kick to front crawl performance from its influence on longitudinal body rotation has not been thoroughly investigated. Fourier analysis was used to examine the impact of the kick on segmental and whole body angular momentum about the body's longitudinal axis in fourteen elite front crawl specialists swimming at sprint and 400m pace. The third harmonic frequency, representing the effects of the six-beat flutter kick, was greater at sprint than 400m pace in lower limb, upper limb, and whole body angular momentum. The presence of the third harmonic in upper limb and whole body angular momentum indicates that the flutter kick has an influence on longitudinal body rotation. The role of the flutter kick in front crawl performance may be linked to actions of the torso muscles to help control longitudinal body rotation.

Introduction

The flutter kick has the potential to improve the effectiveness of the front crawl stroke by influencing longitudinal rotation to enhance the propulsion from the arm stroke (Watkins & Gordon, 1983) and stabilising the body (Maglischo, 2003); however, empirical investigations of the impact of the flutter kick on longitudinal rotation in front crawl swimming are lacking. Analyses of segmental angular momentum have been used in other sports to explain the role of limb movements for performance; for example in walking and running, the angular momentum of the upper limbs about the body's vertical axis counters the rotation caused by movements of the lower limbs. In this way, the arm swing keeps the body from rotating too far to either side by opposing the rotational effects of the lower limbs (Elftman, 1939; Hinrichs, 1987). The arm swing also improves running economy by contributing to upward propulsion so the ground reaction forces from each stride can be directed in the intended direction of travel (Hinrichs, 1987). The angular momentum of the upper limbs is out of phase with that of the lower body to balance the axial rotations of the lower limbs (Hinrichs, 1990). For the duration of one stroke cycle of the arms (i.e. from entry of one hand to the subsequent entry of the same hand), body roll follows a predominant two-beat rhythm, where the swimmer rolls from one side to the other and back again in a sinusoidal pattern. The flutter kick, on the other hand, tends to follow a six-beat rhythm, with three upbeats and three downbeats of either lower limb for the duration of one stroke cycle (Chollet et al., 2000). Due to the differences in frequencies between the two-beat rhythm of body roll and the six-beat rhythm of the flutter kick in front crawl, the timing of longitudinal rotation from the flutter kick is not perfectly in phase or out of phase with body roll. A different approach is therefore needed to analyse the effects of the flutter kick on longitudinal body rotation in front crawl. The repetitive nature of front crawl permits the use of Fourier analysis to represent longitudinal body rotation as a Fourier series of harmonic frequencies. The two-beat rhythm of body roll, for instance, can be represented by the first harmonic frequency while the six-beat rhythm of the flutter kick can be represented by the third harmonic frequency (Sanders & Psycharakis, 2009). In this way, Fourier analysis can be used to investigate the transmission of motion from the flutter kick to the rest of the body by examining the amplitude of the third harmonic in longitudinal angular momentum. Since the speed and vertical amplitude of the foot are greater in faster swimming paces than at slower swimming paces (Kelly de Jesus et al., 2016), a comparison of the harmonic frequencies in the angular momentum signal at different swimming speeds would provide further information about the influence of the flutter kick on longitudinal body rotation. Fourier analysis was therefore used in this study to examine the frequency components of angular momentum data obtained from elite swimmers swimming at two different front crawl speeds to explore the impact of the flutter kick on longitudinal rotation.

Methods

The methods for data acquisition for this study were the same as those in Chapter 3. Digitised three-dimensional coordinate data of sixteen body segments of fourteen elite male Scottish front crawl specialists (age: 17.50 ± 1.91 years; height: 181.89 ± 5.47 cm; mass: 72.45 ± 6.86 kg) previously collected for studies of McCabe et al. (2011) and McCabe and Sanders (2012) were analysed. Participants were either sprint (50m) or middle distance (400m) swimmers who had specialised in front crawl for a minimum of two years, were not currently injured or recovering from injury, and held a short course personal best time of less than 24.60s for 50m or less than 4min10s for 400m. The data comprised one stroke cycle (SC), defined as the moment of hand entry into the water to the subsequent entry of the same hand, from four 25m sprint trials. From a 400m effort, one SC from the first 25m length of each 50m lap was selected for laps 2, 3, 4 and 5, totalling four observations at 400m pace. These were selected to align with previous findings that laps 1, 7 and 8 were consistently different for laps 2-6 (McCabe & Sanders, 2012). Lap 6 was excluded to further minimise the effect of fatigue on swimming technique.

Body segment parameters required for calculation of segment and whole body centres of mass and angular momentum were those obtained by McCabe (2008) using the “eZone” program (Deffeyes & Sanders, 2005) based on the elliptical zone method established by Jensen (1978). The body segment parameter data and manually digitised position data from each trial were then entered into a bespoke MATLAB (Mathworks, Inc.) analysis program written by the fourth author to calculate segmental and whole body centre of mass at each point in the SC. An additional 30 frames at each end of the SC were extrapolated by reflection to prevent data loss during filtering. Fourier transform with a 6 Hz cut-off was used to smooth the data. SC length was standardized to 201 points using Fourier transform and inverse transform so that each datum represented a half percentile of the SC (i.e. 0-100%).

Angular momentum of the lower limbs (sum of local and transfer terms of the left and right foot, shank, and thigh), upper limbs (sum of local and transfer terms of the left and right hand, forearm, and upper arm), and whole body were calculated about the longitudinal axis of the body's centre of mass for each ith percentile of the SC:

$$H_{si} = \sum HL_{si} + \sum HT_{si}$$

where HL_s is the local term, HT_s is the transfer term, and H_s is the angular momentum of each group of *s* segments.

HL_s and HT_s were calculated using the Newtonian equation (i.e. $H = I\omega$) as the product of moment of inertia and angular velocity of each segment about its own centre of mass (HL_s) and about the longitudinal axis of the body's centre of mass (HT_s), respectively.

A Fourier analysis was used to decompose the angular momentum signals into the first three harmonic frequencies (see Kreyszig (2006)). In front crawl swimming, the first harmonic (H1) is associated with the two-beat rhythm of body roll and the third harmonic (H3) is associated with the six-beat rhythm of the flutter kick (Sanders & Psycharakis, 2009). The amplitude (*C*) of each *n*th Fourier harmonic frequency was determined as:

$$Cn = (An^2 + Bn^2)^{0.5}$$

where, *An* and *Bn* are the sine and cosine coefficients.

The proportions of average power (i.e. the mean squared value) comprising the first and third harmonic, respectively, were determined as a percentage of angular momentum signals as:

$$2Cn^2$$

Separate paired *t*-tests were used to compare the amplitudes of H1 and H3, independently, in lower limb angular momentum, upper limb angular momentum, and whole body angular momentum between sprint and 400m pace ($\alpha = 0.05$).

Results

Time series data of angular momentum and the corresponding H1 and H3 frequency components are shown in Figure 4-1 for a typical SC at sprint pace and 400m pace. Average power of H1 and H3 in each angular momentum variable is presented in Table 4-1. H3 dominated lower limb angular momentum, comprising almost 90% of the signal at sprint pace and over 70% at 400m pace. Though H1 comprised the majority of upper limb angular momentum (approximately 75%), H3 accounted for approximately 17% of upper limb angular momentum at both paces. H3 was over 40% of whole body angular momentum at sprint pace and more than 25% at 400m pace. Figure 4-2 shows the amplitudes of H1 and H3 at sprint and 400m pace. H1 in lower limb angular momentum was greater at 400m pace ($p < 0.05$), while H1 in upper limb angular momentum was greater at sprint pace ($p < 0.01$). There was no difference in H1 amplitude in whole body angular momentum. H3 was greater at sprint pace for all angular momentum variables ($p < 0.05$).

Discussion

This study demonstrated the use of Fourier analysis to illustrate the impact of the flutter kick on longitudinal body rotation. At both sprint and 400m pace, the flutter kick had a notable influence on upper limb and whole body angular momentum. The differences in H3 of lower limb angular momentum between paces observed in this study (Figure 4-2) aligns with findings that the six-beat flutter kick is associated with faster swimming (Chollet et al., 2000). It could be expected that the size of the difference in H3 of upper limb angular momentum between paces would be similar to the difference in H3 of lower limb angular momentum; however, there was a much smaller disparity between the paces of H3 in upper limb than in lower limb angular momentum, indicating that the torso muscles have a role in controlling longitudinal rotation from the flutter kick. A “filtering” of the six-beat rhythm by the torso muscles may diminish the amount of rotation transferred from the lower limbs to the upper limbs. Furthermore, this “filtering” effect seems to be more prevalent at sprint pace, suggesting a greater demand on the torso muscles in faster swimming. Identification of torso muscle activation profiles in front crawl is required to test this hypothesis.

The large standard deviations in average power of angular momentum amplitude at 400m pace compared to sprint pace (Table 4-1) were likely produced by different motor patterns between participants. Deschodt, Arsac, and Rouard (1999) proposed some swimmers are ‘leg-dominant’ and tend to use their flutter kick more than other swimmers while some swimmers are ‘arm-dominant’ and tend to rely on their arm stroke more than their flutter kick. The shapes of the lower limb angular momentum time series graphs were similar between swimmers at 400m pace, despite differences in the amplitudes of the third harmonic frequency in lower limb angular momentum between swimmers at 400m pace.

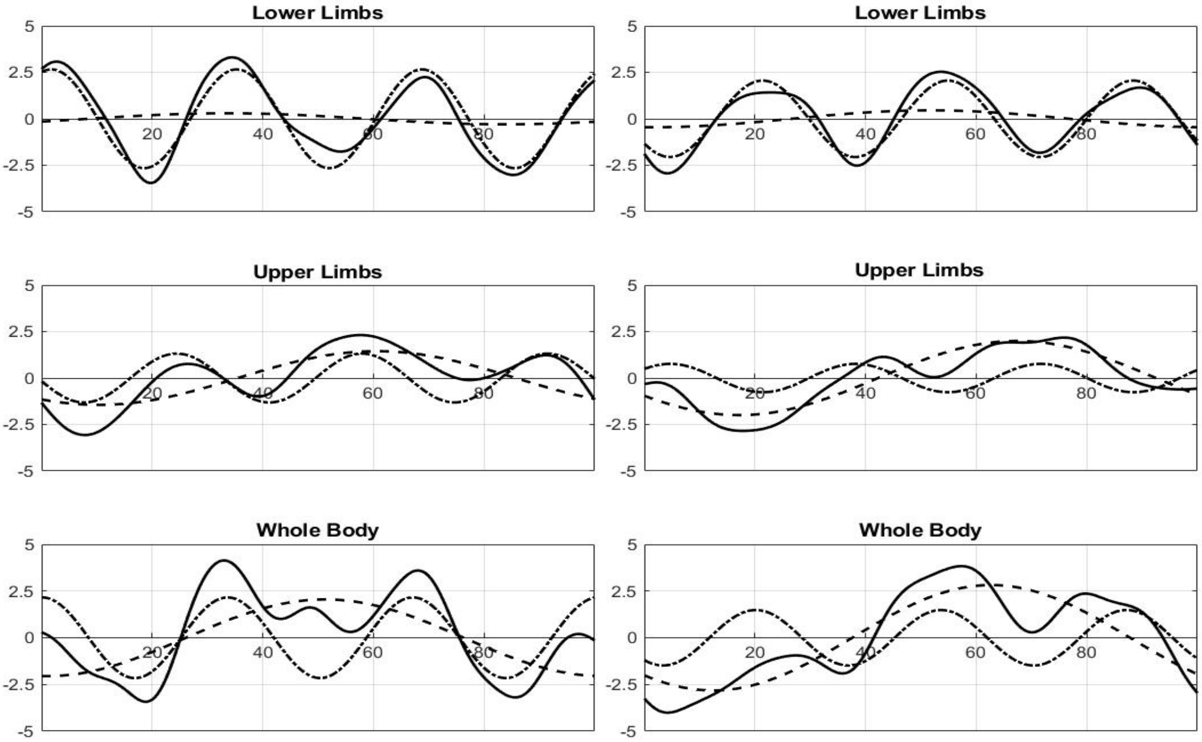


Figure 4-1 Time series of angular momentum (kg·m^2/s) for one stroke cycle at sprint (left) and 400m pace (right). Solid lines show angular momentum, dashed lines are the first harmonic frequency (H1), and dash-and-dot lines are the third harmonic frequency (H3) for each signal.

Table 4-1 Mean (*SD*) of amplitude (%power) of the first (H1) and third (H3) harmonic frequency in lower limb (LL), upper limb (UL), and whole body (WB) angular momentum.

		H1		H3	
		Sprint	400m	Sprint	400m
LL	Mean	2.9%	14.6%	89.1%	71.1%
	SD	*2.4%*	*13.0%*	*5.7%*	*17.9%*
UL	Mean	75.6%	74.6%	17.1%	16.9%
	SD	*9.2%*	*7.6%*	*8.7%*	*6.6%*
WB	Mean	48.7%	64.9%	41.5%	27.1%
	SD	*12.2%*	*13.2%*	*14.8%*	*13.7%*

Though the upper body does not rotate about the longitudinal axis with a six-beat rhythm in experienced swimmers, there was a clear impact of the flutter kick on upper limb angular momentum in this study. The presence of the third harmonic in upper limb angular momentum could have been a byproduct of the “stabilising” role of the flutter kick (see Watkins and Gordon (1983)). The rotation produced by the flutter kick, though its purpose may have been to control torso rotation, was also transferred to the upper limbs. Similar to the benefits of the arm swing in running, the flutter kick could produce a countering effect to control longitudinal torso rotation in front crawl. In this way, the flutter kick could improve the effectiveness of the stroke by helping swimmers direct propulsion from the arms towards the intended swimming direction. In contrast, swimmers may also use the movements of the lower limbs to facilitate longitudinal rotation. Yanai (2003) proposed that fluid forces from the flutter kick contribute to longitudinal rotation, allowing swimmers to generate more forward propulsion from the arm stroke rather than “wasting” fluid forces from the arms to drive body roll. In the current study, a portion of the angular momentum swimmers generated with their flutter kick could have been transferred to the torso, producing rotation about the body’s longitudinal axis. The transfer of momentum from the lower limbs to the torso may have contributed to the reduction in H3 amplitude in upper limb angular momentum compared to lower limb angular momentum. Further investigation is needed into the timing and sequencing of lower limb movements and longitudinal body rotation to improve understanding of the different roles of the flutter kick in front crawl performance.

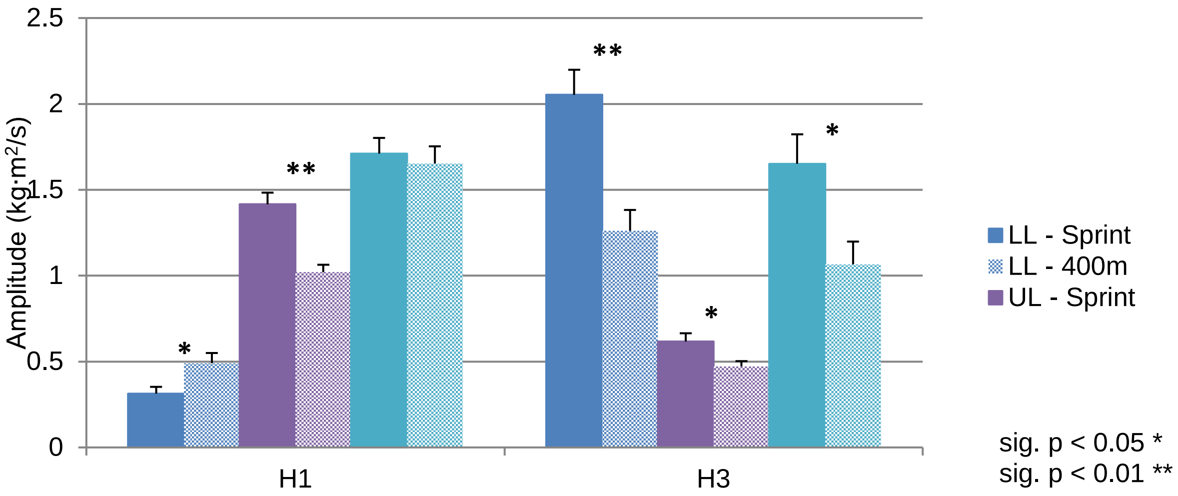


Figure 4-2 Mean H1 and H3 amplitude in angular momentum at sprint and 400m pace. Error bars represent standard error.

Conclusion

Fourier analysis is a powerful tool that can be used to determine the impact of segmental motion on body rotation. The findings suggest an important role of the torso muscles in controlling longitudinal rotation from the flutter kick in front crawl. Furthermore, the impact of the flutter kick on longitudinal body rotation presented here indicates that lower limb movements could be help control body roll. The findings from this study provide a foundation for discussions with coaches and athletes to maximise performance.

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CHAPTER 5:

Torso muscle electromyography in middle-distance and sprint pace front crawl swimming

Foreword

The differences observed in torso twist range and velocity between sprint pace and 400m pace in Chapter 3 suggested that torso muscle demands may be higher at faster swimming speeds. Furthermore, the torso muscles may play a role in the "filtering" (i.e. a reduction in the amplitude) of the rotation transferred from the lower limbs to the upper limbs observed in Chapter 4. The following study was designed to investigate the differences in torso muscle activity between 400m and sprint pace front crawl and to explore the associations between torso muscle activity and body rotation about the longitudinal axis. Findings from this study will improve understanding of the demands on the torso muscles in front crawl swimming.

A portion of study in this chapter was accepted for an oral presentation submitted to the 37th International Conference on Biomechanics in Sports 2019 held in Oxford, Ohio, USA 22-26 July 2019 (Appendix H):

> **Andersen, J T**.; Sinclair, P; Fernandes, R; Vilas-Boas, J P; and Sanders, R (2019) Do the torso muscles produce torso twist in front crawl?, *ISBS Proceedings Archive*: Vol. 37: Iss. 1, Article 83. Available at: https://commons.nmu.edu/isbs/vol37/iss1/83.

Introduction

The relationship between torso muscle activity and axial rotation of the spine (McGill, 1991; Pope et al., 1986) and the necessity for swimmers to generate and control longitudinal rotation between the upper and lower torso in front crawl (Andersen, Sinclair, McCabe, & Sanders, 2018; Psycharakis & Sanders, 2010; Sanders & Psycharakis, 2009) indicate that the torso muscles may play an important role in front crawl swimming. Little is known, however, about relationships between torso muscle activity and body rotation about the longitudinal axis in front crawl. Few scientific papers have been published in which torso muscle activity of competitive front crawl swimmers was studied (Martens, Figueiredo, et al., 2015). Further, the contribution of the torso muscles to rotation between the upper and lower torso in front crawl has never been investigated. The lack of information about the patterns of torso muscle activity limits our understanding of the demands in front crawl swimming.

Rotations of the shoulders and hips about the body’s longitudinal axis, known respectively as shoulder roll and hip roll, follow a sinusoidal rhythm in front crawl (Sanders & Psycharakis, 2009); however, shoulder roll and hip roll are not exactly synchronised. The range of shoulder roll is greater than the range of hip roll regardless of swimming speed (Cappaert et al., 1995; Yanai, 2003) and timing differences of shoulder and hip roll can exist in individual swimmers (Psycharakis & Sanders, 2008). These differences between shoulder and hip roll indicate a relative independence in the rotation of the upper and lower torso that requires twist within the torso. Considering the important role the torso muscles play in generating torso twist and providing stability during twisting motions of the spine (McGill, 1991), the torso muscles may be involved in the twisting action between the upper and lower torso in front crawl swimming.

Previous quantitative analysis (Chapter 3) revealed greater range and velocity of torso twist, reflected in the relative difference between shoulder and hip roll angle, at sprint pace (1.81 m/s) than at middle-distance pace (1.46 m/s) in national and international front crawl specialists. These findings suggest that longitudinal rotation between the upper and lower torso is larger and more rapid as swimming speed increases. Torso muscle activity is associated with both the magnitude and speed of rotation between the upper and lower torso (Kumar et al., 1996; Marras et al., 1998), which could imply that changes in the range and velocity of torso twist between swimming paces place different demands on the torso muscles. However, changes in torso twist could be produced by external torques from the arm stroke and the flutter kick without an accompanying change in torso muscle activity. Torso muscle activity at different front crawl swimming paces requires investigation to determine whether torso muscle demands change with the range and velocity of torso twist at different swimming speed.

Longitudinal body rotation in front crawl improves propulsion generation from the arms (Kudo, Sakurai, Miwa, & Matsuda, 2017) and reduces the risk of shoulder injury (Yanai & Hay, 2000). Swimmers are therefore likely to benefit from improving their ability to control rotation between the upper and lower torso. This may be why dry-land exercises for swimmers tend to involve twisting movements of the torso. However, it is unclear whether the torso muscles or other mechanisms produce this twist. For example, the actions of the upper and lower limbs that produce body rotation about the longitudinal axis (Yanai, 2004) could produce torso twist from differences in the torques acting on the upper and lower torso. This gives reason to question whether exercises typically used in dry-land training that involve active torso twisting are specific to the needs of swimmers.

The acceleration of the thorax with respect to the pelvis depends on resolution of the equation of angular motion $\alpha = \Sigma T/I$ where T is torque acting on the thorax and I is the moment of inertia of the upper body including the thorax, head, and upper limbs. The torques acting on the thorax comprise the torque produced by internal reaction moments about the shoulder due to the actions of the arms, the external buoyancy and gravitational forces, and internal torques produced by the actions of the torso muscles. The angular motion of the pelvis depends on the internal torques due to the actions of the lower limbs, external buoyancy and gravitational forces, and the reactions to the actions of the torso muscles. Angular momentum could also be transferred passively between the upper and lower torso through connective tissue and elastic components of the torso muscles. Although the contributions of the forces to torque are not readily obtainable in swimming, knowledge of the relationship between torso muscle activity and rotational acceleration of the thorax with respect to the pelvis, or ‘torso twist acceleration’, may provide insights into the roles of the torso muscles in producing torso twist or in stabilising the torso.

The purpose of this investigation was to compare torso muscle activity in front crawl swimming at middle-distance and sprint pace and to assess the relationships between torso muscle activity and torso twist acceleration. It was hypothesised that torso muscle activity is higher at sprint pace than at middle-distance pace. The findings will fill some of the gap in our understanding of the physical requirements of the torso muscles in front crawl swimming. Coaches and athletes could use these findings to develop programs to condition the torso muscles that are specific to the demands of front crawl swimming across different event distances.

Methods

Participants

Fifteen male competitive swimmers participated in this study (Table 5-1). Participants were regional and national level Portuguese swimmers with at least five years of competitive swimming experience and trained between five and eight times per week at the time of data collection. Three participants preferred to breathe to their left side and twelve preferred to breathe to their right side. Participants were not recovering from injury that prevented them from normal swimming training. The procedures were approved by the Ethics Committee of the Faculty of Sport from the University of Porto. The procedures were explained to each participant in Portuguese (Appendix A) before written informed consent was received (Appendix B). For participants under the age of 18, written consent was also received from a parent or guardian.

Table 5-1. Characteristics of the fifteen male competitive swimmers included in the current study.

	Mean	**SD**
Age (years)	20.47	4.82
Weight (kg)	69.59	10.97
Height (m)	1.78	0.09
50m long course best time in previous 12 months	25.88s	1.27s
400m long course best time in previous 12 months	4min26s	14.59s

Procedures

Procedures for data collection and roles allocated to research assistants are outlined in Appendices C1-C12. Each data collection took about two hours from the moment the participant arrived to the end of data collection. Testing was conducted in a 25m indoor swimming pool. Participants completed a standardised 1000m warm up (Appendix C3 and C4) that included 4x50m at a self-selected speed that was as close to their 400m race pace as possible. The 50m repetitions were hand-timed and recorded by a student swim coach from the university to ensure participants were capable of repeating submaximal efforts at a consistent speed. Upon completion of the warm up, participants immediately exited the pool, dried off, and were fitted with EMG apparatus and motion capture markers in an air-conditioned room with direct access to the pool deck. EMG electrode and body landmark positions were identified for all participants by the same researcher.

Instrumentation – Electromyography

EMG data were recorded from internal oblique, external oblique, rectus abdominis, lumbar erector spinae, and thoracic erector spinae from the right side using BIOPAC hardware and AcqKnowledge software (BIOPAC Systems, Inc) on a computer dedicated to EMG data acquisition. The skin was shaved and cleansed with alcohol to reduce signal impedance (Clancy et al., 2002; Konrad, 2005). Ag-AgCl surface electrodes were adhered to the skin over the muscle belly with an inter-electrode distance of 2.5cm in parallel with the muscle fibres at the locations outlined in Table 5-2 (see also Appendix C12). A reference electrode was placed on the posterior superior iliac spine (PSIS). Figure 5-1 and Figure 5-2 show the locations of the abdominal electrodes and back and reference electrodes, respectively. Waterproofing techniques, adapted from Vitor et al. (2016), ensured participants were safe from electric shock and the EMG equipment was protected from water damage. Once in place, electrodes were covered with waterproof adhesive (Opsite Flexfix Transparent Adhesive, Smith & Nephew Inc.). It was found during pilot testing that this helped prevent the electrodes from detaching when participants began to sweat from the temperature on the pool deck. A small cut was made in the adhesive over the Ag-AgCl diode and the EMG cables were connected. The quality of the signal was tested with submaximal flexion, extension, and twisting moments produced by the participant. If signal quality was poor, the affected electrodes were removed, the skin prepared once again, new electrodes attached, and the signal tested a second time. Signal quality issues were always resolved once electrodes were replaced. The entire electrode-and-cable complex was then covered with Opsite Flexfix adhesive. Preamplifiers were enclosed in epoxy resin to prevent water from destroying the equipment (Figure 5-3). The EMG cables were taped to the skin to reduce noise artefact and bound together to create an ‘umbilical cord’. EMG was sampled at 2000 Hz with a 16-bit analogue to digital conversion. Myoelectric signals were amplified once using AD621 preamplifiers close to the electrode site and a second time using an amplifier box located on the pool deck (total gain = 1100) with a common mode rejection ratio of 110 dB to reduce noise artefact.

Table 5-2. EMG recordings and electrode placements.

Muscle	**Approximate location of electrodes** after McGill et al. (1996) and McGill, Andersen, and Cannon (2015)
Internal oblique	Diagonally, medial to linea semilunaris and superior to inguinal ligament at level of ASIS
External oblique	Diagonally, 3cm lateral to linea semilunaris at level of umbilical
Rectus abdominis	Vertically, 3cm lateral to umbilical

Lumbar erector spinae	Vertically, 3cm lateral to spine at L3
Thoracic erector spinae	Vertically, 5cm lateral to spine at T9

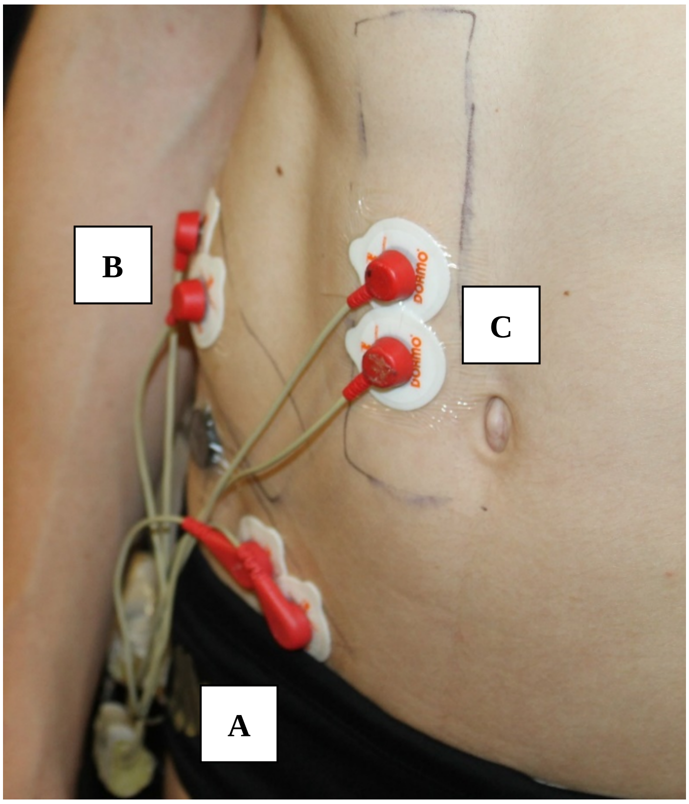

Figure 5-1. Electrode placement for abdominal muscles: (A) internal oblique, (B) external oblique, (C) rectus abdominal.

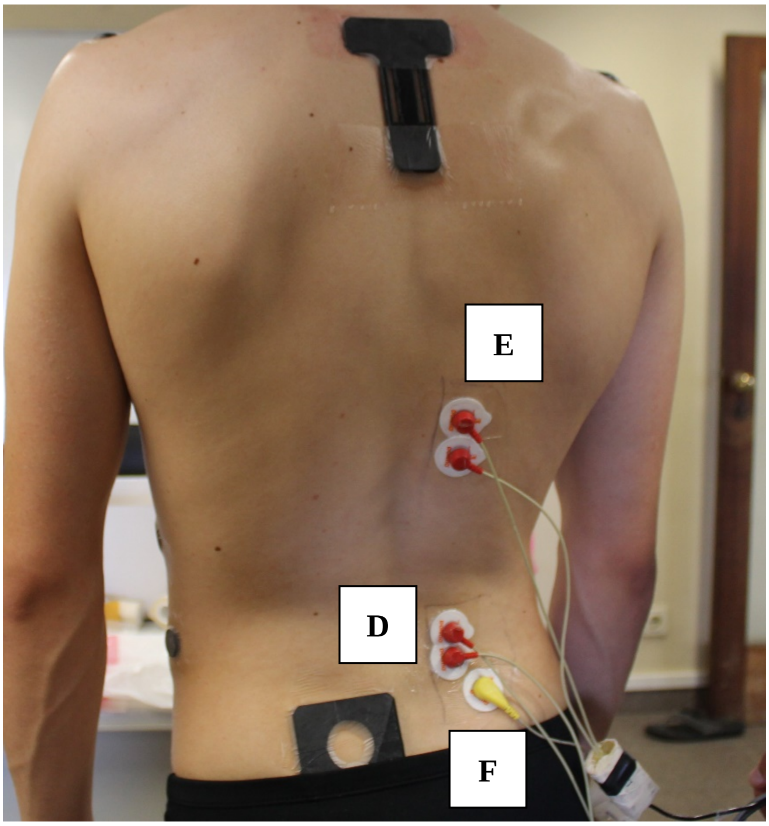

Figure 5-2. Electrode placement for back muscles and reference electrode: (D) lumbar erector spinae, (E) thoracic erector spinae, (F) reference electrode (yellow connector).

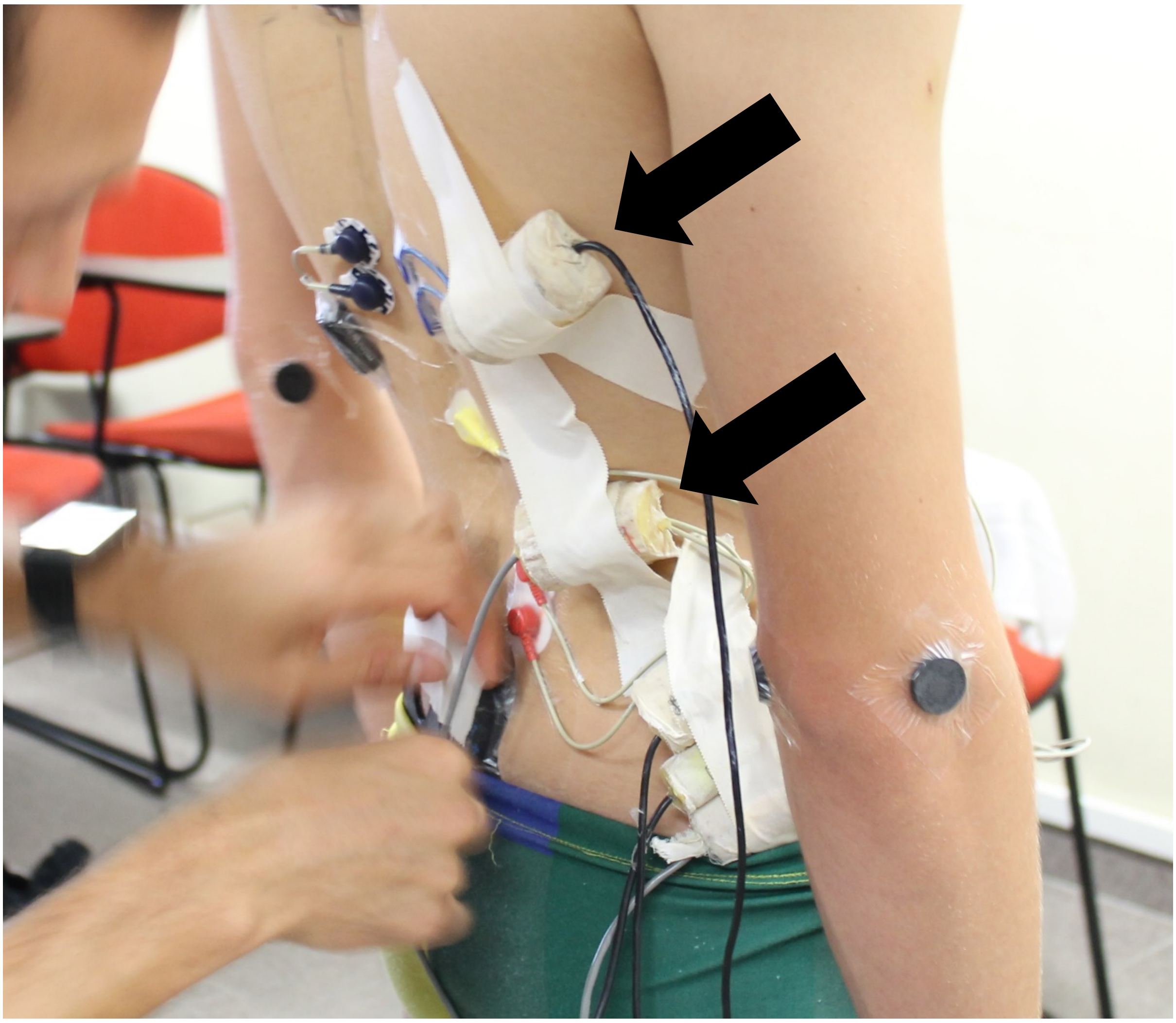

Figure 5-3. Preamplifiers were enclosed in epoxy resin for waterproofing (black arrows). Magnetic markers were positioned at least 5cm away from pre-amplifiers and electrodes.

Instrumentation – Motion capture

Participants' motions were captured at 100 Hz with the Qualisys Motion Capture System (Qualisys AB, Göteborg, Sweden) using 11 above water and 6 underwater cameras with two separate computers. The Qualisys software synchronises the 'slave' computer for the underwater cameras with the principal computer for the above water cameras. The system was calibrated in three steps: calibration of the above water cameras, calibration of the underwater cameras, and a 'dual-media' (i.e. air and water) calibration to synchronise the calibrations of the above and underwater cameras. A T-shaped wand, provided by Qualisys

AB, fitted with two markers on the tips of the top of the 'T' was used to calibrate the system. A 60 to 90s calibration trial was recorded while a researcher swam and slowly waved the wand above the water to calibrate the above water cameras in the space where the calibrated volume would be produced. The researcher repeated this process below the water surface during a 60 to 90s calibration trial by waving the wand underwater to calibrate the underwater cameras directly below the space where the above water cameras were calibrated. A 30s 'dual-media' calibration trial was then recorded while the researcher swam waving the wand with one marker in the space calibrated for the above water cameras and one marker in the space calibrated for the underwater cameras. The purpose of the 'dual-media' calibration was to orient the calibration volume of the below water cameras to the location of the calibration volume of the above water cameras. The three-step calibration process produced a calibrated volume with approximate dimensions of 1.7 m in width, 6.4 m in length, 1.4 m in height that was located 10m from the start wall and about two thirds underwater and one third above the water. The length of each calibration trial was recommended by Qualisys AB staff during previous collaborations with the researchers from the University of Porto.

The orthogonal global coordinate system was defined by the horizontal X-axis pointing to the swimmer's right, the horizontal Y-axis pointing in the swimming direction, and the vertical Z-axis pointing upwards. The water level in the global coordinate system was recorded while a researcher swam through the calibration volume and held the wand at the water surface for approximately 15s. The researcher swam in a way that minimised the disturbance of the water surface during this trial. Water level recording was repeated if the research team was not confident the wand markers accurately represented the water surface. The vertical component of the water level was subtracted from the vertical component of each individual marker used to track the swimmers' motion (marker locations are listed in the following paragraph). The system was calibrated every morning approximately one hour before data collection commenced and again around midday. By calibrating the cameras twice each day, the resolution and visibility of the markers were optimised for the changed conditions of sunlight at different parts of the day.

Circular bases (20mm diameter) were adhered over the following body landmarks to enable tracking of the participants' movements: left and right acromion, clavicle two thirds of the distance moving from the sternal end to the acromial end (i.e. at the concave/convex junction), lateral aspect of the 10th rib at the mid-axillary line, superior iliac crest, anterior superior iliac spine (ASIS), greater trochanter, medial and lateral epicondyles of the humerus, styloid processes of the radius and ulna, lateral aspect of the head of the 5th metacarpal, medial and lateral points of the knee axis, medial and lateral malleoli, and lateral aspect of the head of the 5th metatarsal. Custom-made T-shaped rigid bodies (80mm x 100mm) were adhered to the skin over the sternum and over the thoracic spine at the level of T3. A square-shaped rigid body (60mm x 60mm) was adhered over the left PSIS. The bases and rigid bodies were created using a 3D printer (A8, Anet) (Fonseca, 2018). Each of the bases were indented with a small neodymium magnet (10mm diameter, 2mm thickness) and three magnets were indented into each of the rigid bodies in which magnetic reflective markers were attached (see below). Participants donned a full-body Speedo FASTSKIN™ swimsuit over the EMG equipment and magnetic bases and rigid bodies. A hole was cut in the back of the FASTSKIN™ at the level of the sacrum to provide an exit point for the EMG leads to minimise disruption of swimming technique (Figure 5-5).

To track the body landmarks covered by the FASTSKIN™ swimsuit, spherical magnetic markers (20mm diameter) created from a custom design (Fonseca, 2018) were connected to the bases and rigid bodies over the swimsuit. The magnetic markers were completely covered with reflective tape (Scotchlite™ SOLAS-Grade 3150-A, 3M™). During pilot testing, it was determined that placing the EMG electrodes and pre-amplifiers 5cm away from the body landmarks and rigid bodies ensured the magnets did not interfere with the EMG signals. Non-magnetic spherical markers (20mm diameter) were connected to flexible bases (35mm diameter) for the body landmarks that were not covered by the FASTSKIN™ swimsuit (i.e. landmarks of the wrists, hands, ankles, and feet). The flexible bases conformed to the natural shape of the participant’s anatomy and were taped to the skin. Reflective tape was used to cover the tip of the distal phalanx of the third digit of each hand and the distal phalanx of the first digit of each foot. Participants also wore a tight-fitting polyester swim cap that was fitted with four reflective markers (Figure 5-4 and Figure 5-5).

[redacted]

Figure 5-4. **Qualisys marker locations – front view.**

Figure 5-5. Qualisys marker locations – rear view. The hole in the swimsuit to allow the EMG cables to exit is also visible.

Testing protocol

Motion capture calibration trials

Participants carefully entered the pool to ensure the EMG and motion capture apparatus remained in place once the magnetic and non-magnetic markers were secured over the body landmarks. Participants then swam to the calibration volume and stood on a metal frame such that they were positioned in the middle of the calibration volume (Figure 5-6). A calibration trial of the participant standing in the anatomical position was captured to create a static model of the thorax and pelvis for calculation of kinematic data (see section titled *Data Processing – Motion Data* below). Participants swam back to the start wall to begin the swimming trials. EMG and motion capture were synchronised using a trigger sent from the Qualisys system to the EMG recording computer.

Figure 5-6. Participant standing on metal frame in the middle of the calibration volume.

Swimming protocol

Participants were asked to swim 4x25m at the same pace as their 4x50m efforts in the warm up which was designed to approximate their 400m race pace. Participants rested in the water for 5min after completing the 400m pace trials before completing 4x25m sprints. Between each 25m trial, participants swam back to the start wall as active recovery and rested passively in-water for 2min before beginning the next trial (Appendix C7 and C8). Each trial began from a push start and participants were required to not breathe as they entered the calibration volume (marked on the bottom of the pool) to avoid effects of breathing on swimming technique (Psycharakis & McCabe, 2011). Participants familiarised themselves with the breath-holding requirement during the 4x50m repetitions in warm up.

Data processing

Electromyography data

The EMG acquisition hardware had a built-in 1000 Hz low-pass anti-aliasing filter that filtered the EMG signal before the data were recorded. The EMG data were further processed using MATLAB. Raw EMG data were band-pass filtered (fourth order Butterworth) between 20 and 500 Hz. This range was chosen to remove low frequency noise associated with cable movement artefact and high frequencies that are not associated with the creation of a torso muscle motor unit action potential (Merletti & Di Torino, 1999; Winter, 2009). The mean of each filtered EMG signal was calculated from one second before to one second after the thorax rotation cycle (i.e. from peak thorax rotation about the longitudinal axis to one side to the subsequent peak thorax rotation about the longitudinal axis to the same side – see *Motion Data* section below for full description of kinematic variable calculations). EMG data were 'de-meaned' to remove potential bias (i.e. DC shift) by subtracting the mean of the filtered EMG signal from the filtered EMG signal. The 'de-meaned' signals were then full-wave rectified for further processing and analysis (see *Data and Statistical Analysis* below).

Motion data

Spline filtering algorithms in Qualisys Track Manager (Qualisys AB, Göteborg, Sweden) were used to gap-fill marker trajectories. The researcher's decision to fill a gap was based on how well the gap-fill resembled the pattern of movement from a subjective estimation and the smoothness of the movements in the frames immediately before and after the gap. Gaps were only filled if the researcher was confident that the gap-filled marker trajectories would accurately represent the measurements of the marker trajectories from the motion capture cameras. Otherwise, gaps were not filled and the trial was excluded from analysis.

Motion data were entered into Visual 3D (C-Motion) for filtering and to calculate kinematic variables. The thorax was defined with the left and right acromion and rib markers and was tracked using the three markers on the sternum rigid body. The pelvis was defined with the left and right superior iliac crest and greater trochanter and tracked using the left and right superior iliac crest, greater trochanter, and ASIS. It was necessary to have redundancy in tracking markers on the pelvis due to issues of marker occlusion, especially near the water surface. Effort was made to ensure that at least three markers were able to be tracked for reconstruction of the thorax and pelvis in as many trials as possible.

Three-dimensional marker data were filtered with a fourth order low-pass Butterworth filter. A 6 Hz cut-off was deemed appropriate from residual analysis that was conducted according to methods described by Winter (2009) using custom written MATLAB code. Thorax and pelvis angular displacements about the global horizontal axis in the swimming direction were calculated using the angles between the global Y-axis pointing in the swimming direction and the local coordinate systems of the thorax and pelvis segments, respectively, and resolved in the global coordinate system. Torso twist angle was then the difference between thorax and pelvis angular displacements, resolved in the pelvis coordinate system (see Appendix D for a list of Visual 3D filtering and data processing commands). Positive and negative thorax and pelvis angles represent counter-clockwise and clockwise rotation, respectively, when viewing the swimmer head-on. Positive torso twist indicates the thorax was rotated counter-clockwise with respect to the pelvis and negative torso twist indicates the thorax was rotated clockwise with respect to the pelvis. Torso twist acceleration was calculated as the second time derivative of torso twist angle using central differentiation. One cycle of thorax rotation, defined from peak counter-clockwise thorax rotation to the subsequent peak counter-clockwise thorax rotation, was selected for analysis from each 25m trial at 400m and sprint pace.

Data and statistical analysis

Swimming velocity was determined by dividing horizontal displacement of the thorax by thorax rotation cycle time (m/s). Statistical tests were performed in IBM SPSS Statistics 24, unless otherwise stated, using a significance level of $\alpha = 0.05$. The intra-class correlation of the times measured for each 4x50m repetition during warm up was tested in SPSS to determine the reliability of the swimmers' times. A single-rating, absolute agreement, two-way mixed random effects model (Koo & Li, 2016) was used because times were measured by the same student swim coach and it was assumed the student coach possessed timing skills characteristic of most swim coaches.

Differences in torso muscle activity between swimming speeds

Across all participants, twelve trials at 400m pace and fourteen trials at sprint pace could not be included for analysis due to EMG signal 'drop-out' and marker occlusion that prevented tracking of the thorax for the duration of one complete cycle of thorax rotation during data collection. The gaps in the thorax marker data during these trials could not be filled with confidence, as described in the section *Data Processing – Motion Data*. Therefore, 48 trials at 400m pace and 46 trials at sprint pace were used to investigate the effects of swimming speed on torso muscle activity (see Appendix E for the number of trials included for each individual participant).

Full-wave rectified EMG data were integrated (in µV·s) to find the 'area under the curve' for the duration of the cycle of thorax rotation in MATLAB. Integrated EMG was then divided by the cycle time to provide a measurement in µV of average muscle activity of each muscle over the entire cycle for each swimming trial (iEMG) (Winter, 2009, p. 272). A single iEMG score was determined for each participant at 400m pace and at sprint pace, respectively, by calculating mean iEMG across trials.

The Shapiro-Wilk test indicated that iEMG scores for rectus abdominis, lumbar erector spinae, and thoracic erector spinae were normally distributed across participants at both paces. Separate paired *t*-tests were used to evaluate the differences between paces in iEMG for these muscles. iEMG scores for internal oblique and external oblique, however, were not normally distributed across participants at sprint pace. Differences in iEMG between paces were therefore evaluated using the Wilcoxon Signed Rank Test for these two muscles as a non-parametric equivalent to the paired *t*-test.

Effect sizes were calculated manually in Excel. For parametric comparisons (i.e. rectus abdominis, lumbar erector spinae, and thoracic erector spinae), Cohen's *d* was used to estimate effect size with the following equation:

Equation 1: $$Cohen's\ d = \frac{\bar{x}_1 - \bar{x}_2}{SD_{pooled}}$$ (J. Cohen, 1988)

where, $\bar{x}_1$ is the mean at sprint pace and $\bar{x}_2$ is the mean at 400m pace. SD_{pooled} was the square root of the average of the squared standard deviations from either pace:

Equation 2: $$SD_{pooled} = \sqrt{\frac{(SD_1^2 + SD_2^2)}{2}}$$

where, SD_1 is the standard deviation at sprint pace and SD_2 is the standard deviation at 400m pace. Effect sizes for parametric paired *t*-tests were interpreted using Cohen's (1988, p. 40) recommendations (small: $d < 0.50$; medium: $d = 0.50$ to 0.80; large: $d > 0.80$).

Non-parametric effect sizes (i.e. internal oblique and external oblique) were calculated manually in Excel as:

Equation 3: $$r = \frac{z}{\sqrt{n}}$$ (Fritz et al., 2012)

where, z is the z-distribution determined by the Wilcoxon Signed Ranked Tests performed in SPSS and n is the number of participants included for each comparison. Effect sizes for non-parametric Wilcoxon Signed Ranked Tests were also interpreted using Cohen's (1988, pp. 79-80) recommendations (small: $r < 0.30$; medium: $r = 0.30$ to 0.50; large: $r > 0.50$).

Average iEMG across all participants and 95% confidence intervals of the true mean (95%CI) were calculated for 400m pace and for sprint pace. Confidence intervals of the true mean provide a range (with a 95% probability in this case) in which the actual mean is likely to occur. Confidence intervals were calculated in Excel as:

Equation 4: $$95\%CI = t_{n-1}\frac{s}{\sqrt{n}}$$

where t_{n-1} is the t-value for n participants at a 95% confidence level (i.e. $p = 0.05$) and s is the standard deviation. As explained above, some EMG channels dropped out during data collection. This resulted in different t_{n-1} and n values when using Equation 4 for different torso muscles at either pace.

Torso muscle activity and torso twist

To calculate torso twist for a given trial, it was necessary that the thorax and pelvis segments were visible for every frame of the thorax rotation cycle. Reconstruction of the thorax and pelvis angular motion for the duration of one complete cycle of thorax rotation was possible in 33 trials at 400m pace and 21 trials at sprint pace (see Appendix E for number of trials included for each individual participant). The relationships between torso muscle activity and the angle and acceleration of torso twist were analysed using only these trials. (Note: The pelvis could not be reconstructed for any trial from three participants at sprint pace because fewer than three pelvis markers were visible for the duration of an entire thorax rotation cycle.)

In addition to calculating average iEMG, full-wave rectified EMG (sampled at 2000 Hz) was integrated over 10ms intervals of the thorax rotation cycle to match the sampling frequency of the motion data (sampled at 100 Hz). Integrated EMG over the 10ms intervals, pelvis angle, thorax angle, torso twist angle, and torso twist acceleration data were standardised to 201 points of the thorax rotation cycle using Fourier transform and inverse transform (Sanders, Gonjo, & McCabe, 2015) such that each datum represented a half percentile (i.e. 0-100%). Integrated EMG was then divided by the maximum value from each trial to produce a percentage of maximum muscle activity (%iEMG) for each percentile of the thorax rotation cycle.

Torso muscle activity and torso twist acceleration

Percent iEMG and torso twist acceleration were averaged for every 5th percentile of the thorax rotation cycle, producing twenty scores for each variable over the entire cycle. Percent iEMG data were not normally distributed according to the Shapiro-Wilk test. Therefore, Spearman Rank-Order correlation tests were used to correlate 5th percentile %iEMG scores with 5th percentile torso twist acceleration scores over the entire thorax rotation cycle. Five separate tests (one for each muscle) were conducted for every individual trial at either pace to explore the relationships between torso muscle activity and torso twist acceleration. The range of the correlation coefficients across trials were analysed and interpreted using Cohen's (1988) recommendations (weak: $r < 0.30$; moderate: $r = 0.30$ to 0.50 strong: $r > 0.50$).

Results

The swimmers' times were highly reliable for the 50m repetitions during warm up (Cronbach's $\alpha = 0.99$). Average swimming velocity was 1.39 ± 0.11 m/s at 400m pace and 1.59 ± 0.09 m/s at sprint pace.

Differences in torso muscle activity between swimming speeds

Average iEMG was greater at sprint pace than at 400m pace ($p < 0.05$) for internal oblique, external oblique, and rectus abdominis with large effect sizes. The differences in average iEMG for lumbar and thoracic erector spinae were not statistically significant (Table 5-3).

Table 5-3. Average integrated EMG of the torso muscles divided by the duration of the cycle of thorax rotation at 400m pace and sprint pace front crawl swimming.

		400m Pace		Sprint Pace		Effect Size
		Mean	95%CI	Mean	95%CI	
Average iEMG (μV)	IO*	86.9	21.3	141.1	48.7	$0.62^{\#}$
	EO*	42.0	14.7	58.4	22.8	$0.52^{\#}$
	RA*	16.7	5.9	38.7	15.6	$1.13^{\wedge}$
	LES	49.5	35.1	48.3	28.6	-0.03
	TES	55.6	20.9	62.3	23.6	0.19

IO = internal oblique
EO = external oblique
RA = rectus abdominis
LES = lumbar erector spinae
TES = thoracic erector spinae

*Greater at sprint pace than at 400m pace ($p < 0.05$)
$^{\#}$Large effect size for non-parametric comparison ($r > 0.50$)
$^{\wedge}$Large effect size for parametric comparison ($d > 0.50$)

Torso muscle activity and torso twist

Time series graphs for thorax angle, pelvis angle, and torso twist angle from every trial that torso twist could be calculated (400m pace: 33 trials, sprint pace: 21 trials) are shown in Figure 5-7. The pelvis and thorax were facing the swimmers' left side at the beginning of the cycle of thorax rotation and rotated in the clockwise direction (when viewing the swimmer head-on) to face the swimmers’ right side before rotating back in the counter-clockwise direction towards the end of the cycle. This produced a single sine curve in thorax and pelvis rotation. A similar sinusoidal pattern has been observed in shoulder roll and hip roll in 200m pace front crawl swimming where the hips and shoulders rotated about the body’s longitudinal axis at the frequency of the arm stroke cycle (Sanders & Psycharakis, 2009).

Three local minima and three local maxima can be seen in pelvis angle in several trials at either pace. These minima and maxima produced a pattern that resembled a sinusoidal rhythm three times the frequency of the sine curve observed in thorax and pelvis rotation. Thorax angle in some trials at either pace also seemed to be influenced by one or more underlying rhythm in addition to the dominant sinusoidal pattern, but to a lesser extent than pelvis angle.

The sine wave that dominated thorax and pelvis rotation can be seen in the torso twist graphs at the bottom of Figure 5-7; however, it appears that the other rhythms present in thorax and pelvis rotation created an interference pattern to produce a wide range of oscillations in torso twist angle across trials at both paces.

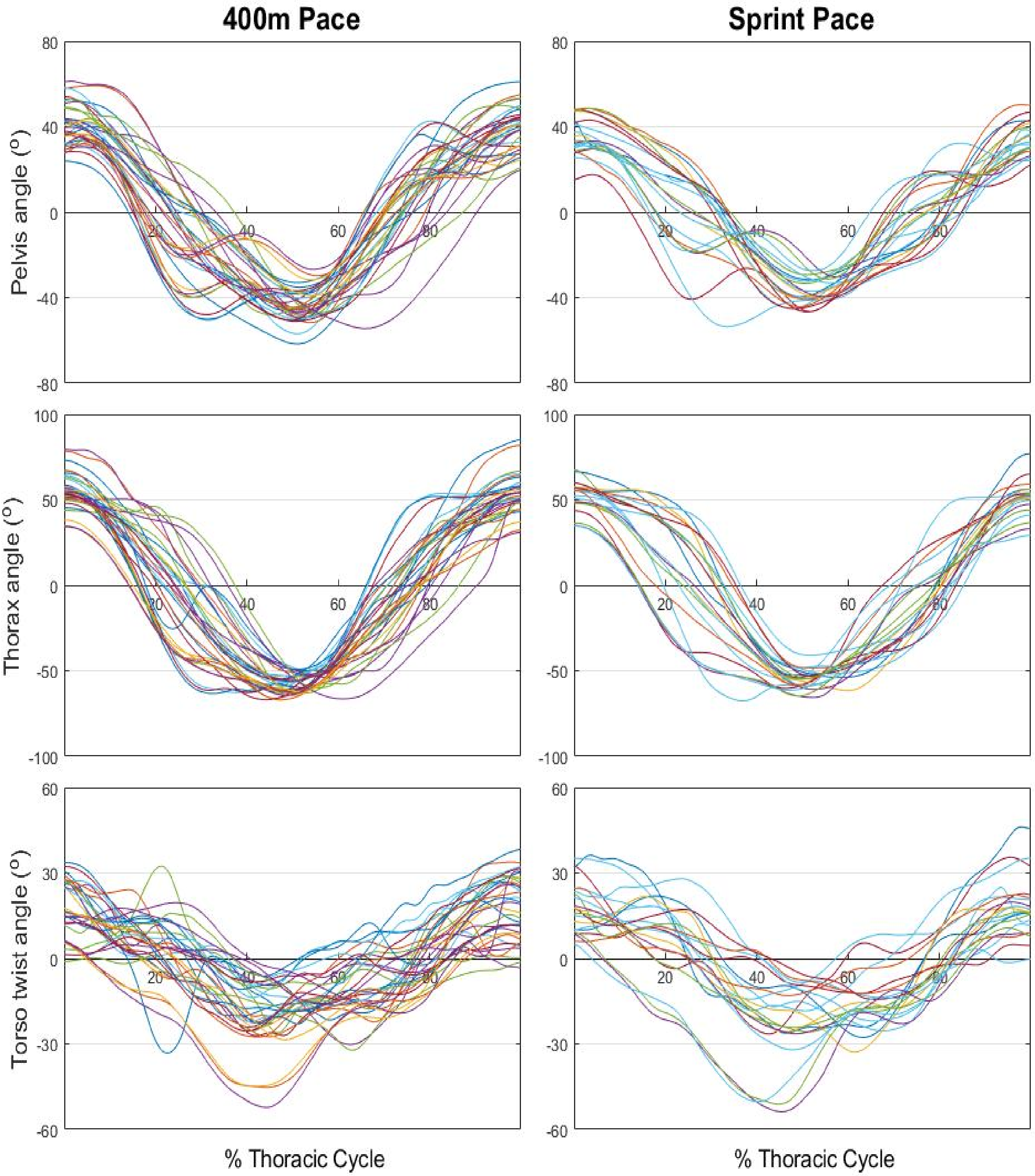

Figure 5-7. Time series graphs of pelvis angle (top), thorax angle (middle), and torso twist angle (bottom) at 400m pace (left) and sprint pace (right). Positive and negative values in the pelvis and thorax graphs indicate rotation in the counter-clockwise and clockwise directions, respectively, when viewing the swimmer head-on. Positive and negative values in the torso twist graph indicate the thorax was rotated counter-clockwise and clockwise, respectively, with respect to the pelvis.

The patterns in torso twist angles were highly variable across trials at both paces. This presented a challenge when comparing trends in the relationships between torso muscle activity and torso twist between participants. In addition to the variability of torso twist patterns between participants, the timing of muscle activity and torso twist angle varied between trials within individual swimmers. Torso twist angle and muscle activity data from all participants are shown as time series graphs in Appendix F. Data from an exemplar participant (P10) were selected to demonstrate the within-subject variability. The graphs in Figure 5-8 show time series data for three trials from P10 at 400m pace (left) and sprint pace (right) of torso twist angle (top graphs) and %iEMG (bottom five graphs). With the exception of external oblique that dropped out for Trial 3 at sprint pace, these three trials contained a complete set of torso twist and EMG data over an entire thorax rotation cycle. All participants showed similar inconsistent patterns of muscle activity and torso twist angle between trials.

Internal oblique activity for P10 increased at times corresponding to 25%, 60%, and near the end of the thorax cycle in each trial, but there were no consistent patterns in the changes of torso twist angle corresponding temporally to these increases in muscle activity (Figure 5-8). For example, when internal oblique activity increased near 25% of the cycle at 400m pace, torso twist angle in Trial 1 was close to zero and decreasing (i.e. the thorax had begun to rotate in the clockwise direction with respect to the pelvis) while in Trial 2 torso twist angle was about 9 degrees and had plateaued.

External oblique activity increased in each trial at both paces around 10% of the cycle just prior to positive maximum torso twist angle (i.e. when the thorax was near peak counter-clockwise rotation with respect to the pelvis). There was a second increase in external oblique activity around 85% of the cycle at both paces; however, in contrast to the burst of activity around 10% of the cycle, these increases did not correspond to changes in torso twist angle in any of the trials (Figure 5-8).

Rectus abdominis activity did not seem to correspond consistently to changes in torso twist angle. At sprint pace for instance, rectus abdominis activity peaked between 80 and 90% of the cycle for Trials 1 and 2 during which time torso twist angle rose steadily in Trial 1 but fluctuated in Trial 2 (Figure 5-8).

Lumbar erector spinae activity at sprint pace increased from about 70% of the cycle and remained high until the end of the cycle for each trial, but the changes in torso twist angle were different for each trial during this part of the cycle (Figure 5-8). The increase in lumbar erector spinae activity at the beginning of the thorax cycle was presumably a continuation from the previous cycle and the patterns in torso twist were different between trials for this part of the cycle.

The increase in thoracic erector spinae activity between 5 to 35% of the thorax cycle at 400m coincided with both counter-clockwise and clockwise rotation of the thorax with respect to the pelvis, showing no obvious pattern between muscle activity and torso twist angle. At sprint pace, thoracic erector spinae activity increased in Trials 1 and 3 but remained low in Trial 2 between 15 and 45% of the cycle while torso twist angle tended to decrease during this part of the cycle for each trial (Figure 5-8).

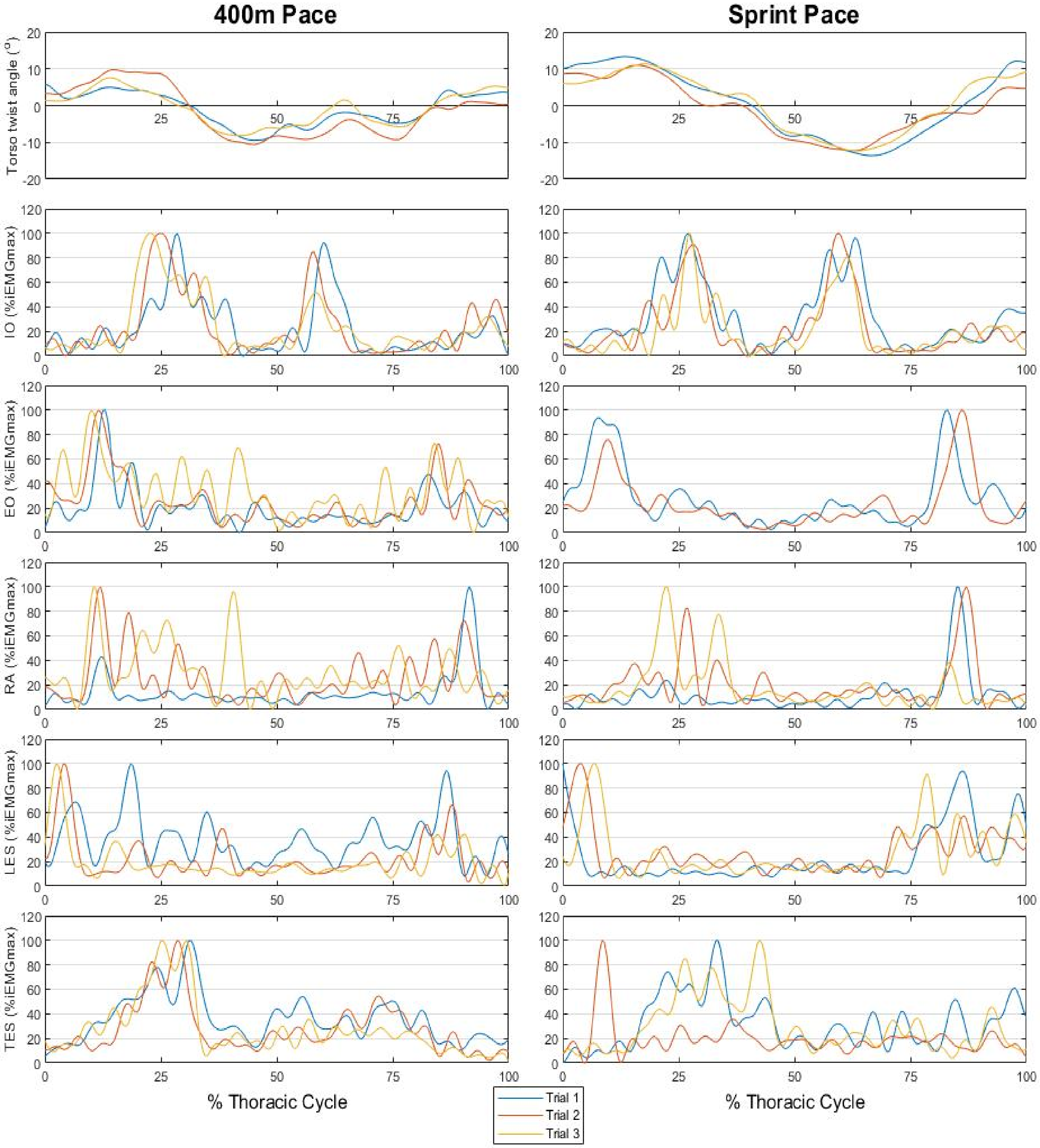

Figure 5-8. Torso twist angle (top) and %iEMG (bottom five) for three trials at 400m pace (left) and sprint pace (right) from an exemplar participant (P10). Positive and negative values in the torso twist graph indicate the thorax was rotated counter-clockwise and clockwise, respectively, with respect to the pelvis.
IO = internal oblique
EO = external oblique
RA = rectus abdominis
LES = lumbar erector spinae
TES = thoracic erector spinae.

Torso muscle activity and torso twist acceleration

Figure 5-9 shows ensemble averages graphs with standard deviations of torso twist acceleration and %iEMG from all trials in which torso twist could be calculated. The effects of pelvis and thorax oscillations can be seen in torso twist acceleration: the direction in which torso twist acceleration acted changed several times throughout the cycle of thorax rotation at both paces. There were two peaks in the ensemble average graphs of internal oblique activity at both paces: one between 20 to 40% and one between 50 to 70% of the cycle (Figure 5-9). During these parts of the cycle, torso twist acceleration acted in both the clockwise and counter-clockwise directions with no obvious pattern with respect to the changes in internal oblique activity. Similarly, the increases in external oblique activity at the beginning of the cycle at both paces and at 80% of the cycle at sprint pace did not seem to relate to changes in torso twist acceleration. There were no clear patterns between torso twist acceleration and the changes of rectus abdominis, lumbar erector spinae, or thoracic erector spinae activity at either pace. The range of correlation coefficients was large for the relationships between %iEMG and torso twist acceleration from individual participants for all muscles at both paces (Table 5-4).

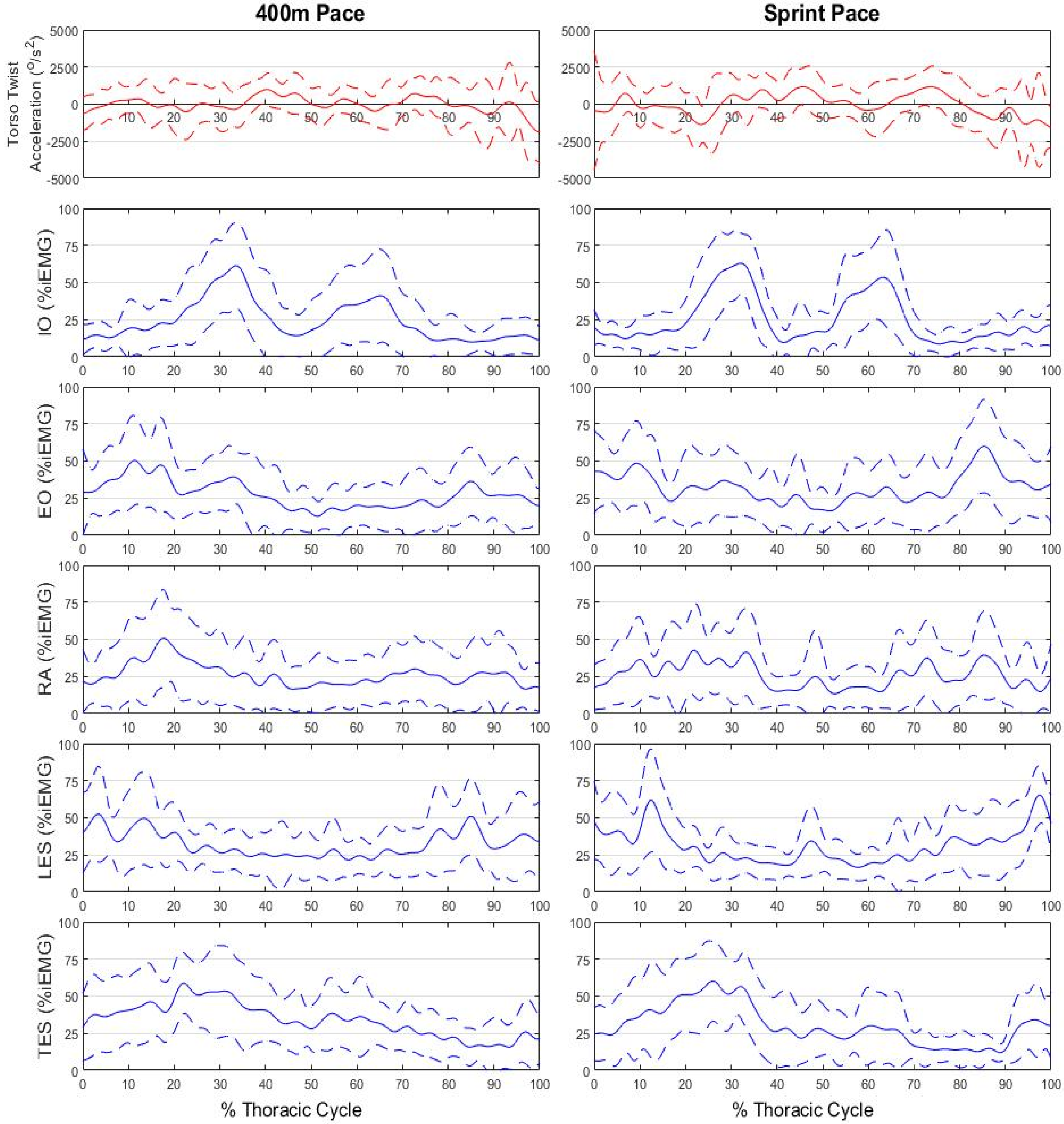

Figure 5-9. Time series graphs of ensemble averages (solid lines) with standard deviations (dashed lines) for torso twist acceleration (top) and %iEMG (bottom five) at 400m pace (left) and sprint pace (right).
IO = internal oblique
EO = external oblique
RA = rectus abdominis
LES = lumbar erector spinae
TES = thoracic erector spinae

Table 5-4. Range of Spearman correlation coefficients (*r*) between 5th percentile scores of torso muscle activity (%iEMG) and 5th percentile scores of torso twist acceleration across trials in which torso twist could be calculated at 400m pace (33 trials) and sprint pace (21 trials).

	Internal Oblique	External Oblique	Rectus Abdominis	Lumbar Erector Spinae	Thoracic Erector Spinae
400m Pace	-0.54 to 0.34	-0.35 to 0.26	-0.53 to 0.56	-0.63 to 0.30	-0.39 to 0.35
Sprint Pace	-0.34 to 0.37	-0.61 to 0.29	-0.32 to 0.39	-0.40 to 0.31	-0.51 to 0.17

Discussion

The purpose of this investigation was to compare torso muscle activity in front crawl swimming at middle-distance and sprint pace and to assess the relationships between torso muscle activity and torso twist acceleration. It was hypothesised that torso muscle activity is higher at sprint pace than at middle-distance pace. This is the first study in the existing literature of the relationships between torso muscle activity and body rotation about the longitudinal axis in front crawl swimming. The findings presented here help develop our understanding of the roles the torso muscles may (or may not) play in front crawl performance.

The higher activity levels in the abdominal muscles at sprint pace than at 400m pace and the lack of statistical differences in the activity of the erector spinae muscles between swimming paces suggest that the oblique and rectus abdominis muscles may play a greater role in front crawl than the erector spinae muscles as increasing swimming speed. While the hypothesis was only partially supported, these findings provide important insights into the contribution of the torso muscles as swimming speed increases. Swimmers preparing for sprint events may benefit from dry-land training that focuses on the abdominal muscles.

Torso twist acceleration did not display a direct relationship with muscle activity at either pace, suggesting that the torques that produce torso twist are mainly from sources other than the muscles of the torso; for example, from the actions of the arms and legs. If torso twist was produced by the torso muscles in front crawl, it would be expected to find more consistent patterns of muscle activity and torso twist acceleration than the patterns observed in Figure 5-9. The inconsistency of muscle activity patterns reported in this study agrees with previous findings of torso muscle activity during front crawl swimming. The variability of the time series graphs of rectus abdominis from the studies by Ikai et al. (1964), Maes et al. (1975), and Clarys (1985) presented in Figure 2-5 is similar to the wide range of muscle activity patterns reported in Figure 5-9 and Appendix F. In addition, Martens et al. (2016) observed high variability of rectus abdominis activity between highly skilled swimmers. Nevertheless, the fact that muscles varied in their activity during the cycle of thorax rotation indicated that the torso muscles may play roles in front crawl, such as stabilising the torso (e.g. in response to internal and external torques from limb movements) and maintaining streamlined posture. Considering the importance of the torso muscles for spine stability during axial torso rotation (Marras & Granata, 1995), there is a possibility that swimmers use the torso muscles to help maintain torso posture in front crawl as their primary role rather than to produce torso twist.

The three local minima and three local maxima in pelvis angle observed in several trials at both paces (Figure 5-7) seemed to produce a rhythm that resembled a pattern of rotation that has been associated with the actions of the six-beat flutter kick (Yanai, 2003). The oscillations in pelvis angle about the dominant sinusoidal pattern may have therefore been produced by torques acting on the pelvis generated by kicking motions (Sanders & Psycharakis, 2009), suggesting that some, if not all, of the oscillations in torso twist angle may not have been the result of torso muscle actions.

While rotation between the upper and lower torso can be generated by the oblique muscles (Gatton et al., 2001; Marras et al., 1998; Marras & Granata, 1995), consistent patterns were not detected between torso twist and internal and external oblique activity. External oblique activity varied throughout the thorax rotation cycle; however, these changes did not seem to be related to torso twist acceleration (Table 5-4). The internal oblique muscle has been shown to produce rotation of the upper torso towards the *ipsilateral* side. Kumar et al. (1996) and Kumar et al. (2003), for instance, found that right internal oblique activity increased as the upper torso rotated towards the right with respect to the pelvis during twisting motions of the torso. In the current study, the thorax was rotating with respect to the pelvis predominantly towards the left side between 20 and 40% of the thorax rotation cycle (Figure 5-7) when right internal oblique activity increased at both paces (Figure 5-9); that is, the upper torso was rotating towards the *contralateral* side when internal oblique activity increased during this part of the cycle. During the increase in internal oblique activity between 50 and 70% of the cycle (Figure 5-9), however, the thorax was rotating predominantly towards the *ipsilateral* side at both paces (Figure 5-7). Internal oblique may have helped to produce torso twist between 50 and 70% of the cycle, though the bursts in internal oblique activity shown in Figure 5-9 could have been related to other parts of the stroke. Hodges, Cresswell, Daggfeldt, and Thorstensson (2000) and Hodges and Richardson (1997a), demonstrated that activity of the oblique muscles precedes rapid movements involving the upper and lower limbs. Hodges and his co-authors of both studies concluded that the torso muscles provide stability to the spine in preparation for limb movements. The bursts in internal oblique activity could have been associated with a specific phase of the arm stroke from one of the upper limbs or one of the kicks from the lower limbs.

Due to changing hydrodynamic and buoyancy torques acting on the arms and legs (Yanai, 2001b, 2004), swimmers must continuously adjust their posture to maintain balance and body alignment (Maglischo, 2003). Rectus abdominis and lumbar and thoracic erector spinae help maintain spine posture and tend to play a stabilising role during twisting motions of the torso (Kumar et al., 2003; Kumar et al., 1996; Marras & Granata, 1995; McGill, 1991; Pope et al., 1986). The varying levels and large standard deviations of activity of these stabiliser muscles observed at both paces (Figure 5-9) and the absence of association between muscle activity and torso twist acceleration (Table 5-4) indicate that the swimmers in this study may have used the torso muscles to help maintain an optimal body position in response to, or in anticipation of, external and internal torques associated with the arm stroke and the flutter kick. Investigation is required into the relationships between the timing of limb movements and torso muscle activity to explore the stabilising role the torso muscles may play in front crawl swimming and the implications for training.

Conclusions

The internal oblique, external oblique, and rectus abdominis muscles may play a greater role in front crawl than the erector spinae muscles as swimming speed increases. Swimmers specialising in sprint events may therefore benefit from dry-land strength training that focuses on the abdominal muscles. Torso twist angle does not seem to be directly associated with torso muscle activity and no relationships were found between torso muscle activity and torso twist acceleration in 400m and sprint front crawl swimming. The torso muscles may be more important for maintaining torso posture and producing spine stability to assist the limbs in generating motion than generating rotation between the upper and lower torso.

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CHAPTER 6:

Discussion and Conclusions

Competitive swimmers take part in dry-land strength training with at least some exercises designed to condition the torso muscles with the expectation that this would contribute to improving front crawl performance (Hibbs, 2011). While dry-land training seems to be a fundamental part of swimming programs, there is little information available to help guide exercise design. The physical requirements placed on the torso muscles during front crawl swimming should be understood to maximise the probability that dry-land training will transfer to swimming performance. The purpose of this thesis was to establish the roles of the torso muscles during front crawl swimming from analysis of rotation about the body's longitudinal axis and torso muscle activity data during sprint and middle-distance front crawl.

Using Movement Patterns to Define Demands

Coaches are encouraged to bear in mind the demands on the torso muscles established in this thesis when designing dry-land strength training. For instance, while torso twist characteristics can guide decisions for improving the specificity of strength training, the data presented in Chapters 3 and 5 do not imply that the range and velocity of torso twist used in front crawl should be repeated in dry-land exercises. The additional joint loads from gravity in land-based movements compared to the same movements executed in an aquatic environment can increase an athlete's injury risk considerably (Biscarini & Cerulli, 2007; Haupenthal, Ruschel, Hubert, de Brito Fontana, & Roesler, 2010; Heywood, McClelland, Geigle, Rahmann, & Clark, 2016). Axial twist of the spine under the load of gravity on land can lead to radial disc delamination (L. W. Marshall & McGill, 2010). Exercises performed in postures that pose less risk for injury can be designed to meet the functional demands of the torso muscles (McGill, 2010; McGill et al., 2009). Rather than prescribing dry-land exercises that require swimmers to produce the magnitude and speed of torso twist in front crawl, exercises should be designed to challenge the torso muscles in similar ways to front crawl swimming.

The first objective of this thesis was to identify the patterns in the range and rate of change of hip roll, shoulder roll, and torso twist. While further research is required to determine the sources of the torques that produce differences in hip roll, shoulder roll, and torso twist between swimming speeds, the findings in Chapter 3 help illustrate that the demands swimmers experience when racing over shorter front crawl event distances may be greater than the demands of racing over longer front crawl distances.

The second objective was to investigate the impact of the flutter kick on rotation about the body's longitudinal axis. In Chapter 4, the use of Fourier analysis provided an indication of the impact of a six-beat rhythm, which is associated with actions of the flutter kick, on upper limb and whole body angular momentum about the longitudinal axis. The lower amplitude of the six-beat rhythm in upper limb angular momentum than in lower limb angular momentum may have suggested that rotation transferred from the lower limbs to the upper limbs was reduced in the swimmers in that study. This finding could indicate that the torso muscles may play a role in controlling rotation produced by lower limb movements.

The third objective was to explore the relationships between torso muscle activity and body rotation about the longitudinal axis. The study in Chapter 5 is the first in the extant literature of these relationships. Though twisting motions of the torso are commonly used in dry-land strength programs for swimmers, the findings in Chapter 5 suggest that the torso muscles may not be responsible for producing torso twist during front crawl swimming. The torso muscles may play more important roles in providing spine stability and maintaining posture than producing rotation between the upper and lower torso.

The final objective of this thesis was to develop swimming-specific guidelines for dry-land strength training of the torso muscles from kinematic and muscle activity patterns in front crawl swimming. Using the findings from the studies in this thesis, recommendations are presented in this final chapter to help swimming and strength and conditioning coaches improve the specificity of dry-land strength training of the torso muscles for swimmers.

The analyses of movement patterns in front crawl in the studies of this thesis generated hypotheses for the roles the torso muscles may play in front crawl swimming. One role of the torso muscles may be to provide stability in preparation for, or in anticipation of, torques associated with upper and lower limb movements. In Chapter 4, it was found that longitudinal rotation associated with motions of the lower limbs is reduced in magnitude before it is transferred to the upper limbs. It was proposed that the torso muscles produce a “filtering” effect that diminishes the magnitude of rotation transferred from the lower limbs to the upper limbs. In Chapter 5, the torso muscle activity patterns were found to be inconsistent both between and within participants. Associations between muscle activity and torso twist acceleration were not found. Consequently, it was proposed that the torso muscles may provide stability to the spine rather than generate torso twist. A stabilising role of the torso muscles is supported by previous reports discussed in Chapter 2 from the few existing studies of rectus abdominis activity during front crawl (Figure 2-5). Another role the torso muscles may play in front crawl swimming is to help maintain posture. The varying levels of torso muscle activity observed in Chapter 5 could have served to help maintain an optimal body position in response to the torques from hydrodynamic forces, buoyancy and gravity forces, and upper and lower limb muscle forces.

Taking these findings into consideration, and bearing in mind the principle of specificity, the following recommendations for designing dry-land training of the torso muscles are offered:

Differences between swimming paces

The findings in Chapter 3 indicated that the magnitude of the torques acting to rotate the upper and lower torso increased as swimming speed increases for the participants in that study. Further, the “filtering” effect of the torso muscles proposed in Chapter 4 seemed to be greater at sprint pace than at 400m pace. The activity levels of the abdominal muscles (internal oblique, external oblique, and rectus abdominis) reported in Chapter 5 were also greater at sprint pace than at 400m pace. These findings indicate that the requirements are higher for the abdominal muscles when swimmers increase their swimming speed. It is therefore plausible that scaling the loads used in dry-land strength training to match an athlete’s swimming pace would improve the specificity of training when preparing a swimmer for a specific event distance. However, this remains speculative since the conclusions from this thesis were inferred from kinematic and EMG data and forces were not quantified.

Stabilising role of the torso muscles

The proposed “filtering” effect of the torso muscles on the rotation from the lower limbs in Chapter 4 could be reproduced in dry-land exercises by challenging swimmers to control rotation produced by the lower limbs. For example, swimmers could be instructed to use the torso muscles to reduce the motion of the pelvis and in the lower torso while performing flutter kicking movements with the lower limbs while lying on the pool deck. The torso muscles could play a stabilising role of the pelvis and spine during this type of exercise which, according to the findings of Chapter 5, may mimic some of the demands on the torso muscles in middle-distance and sprint front crawl swimming (Figure 6-1).

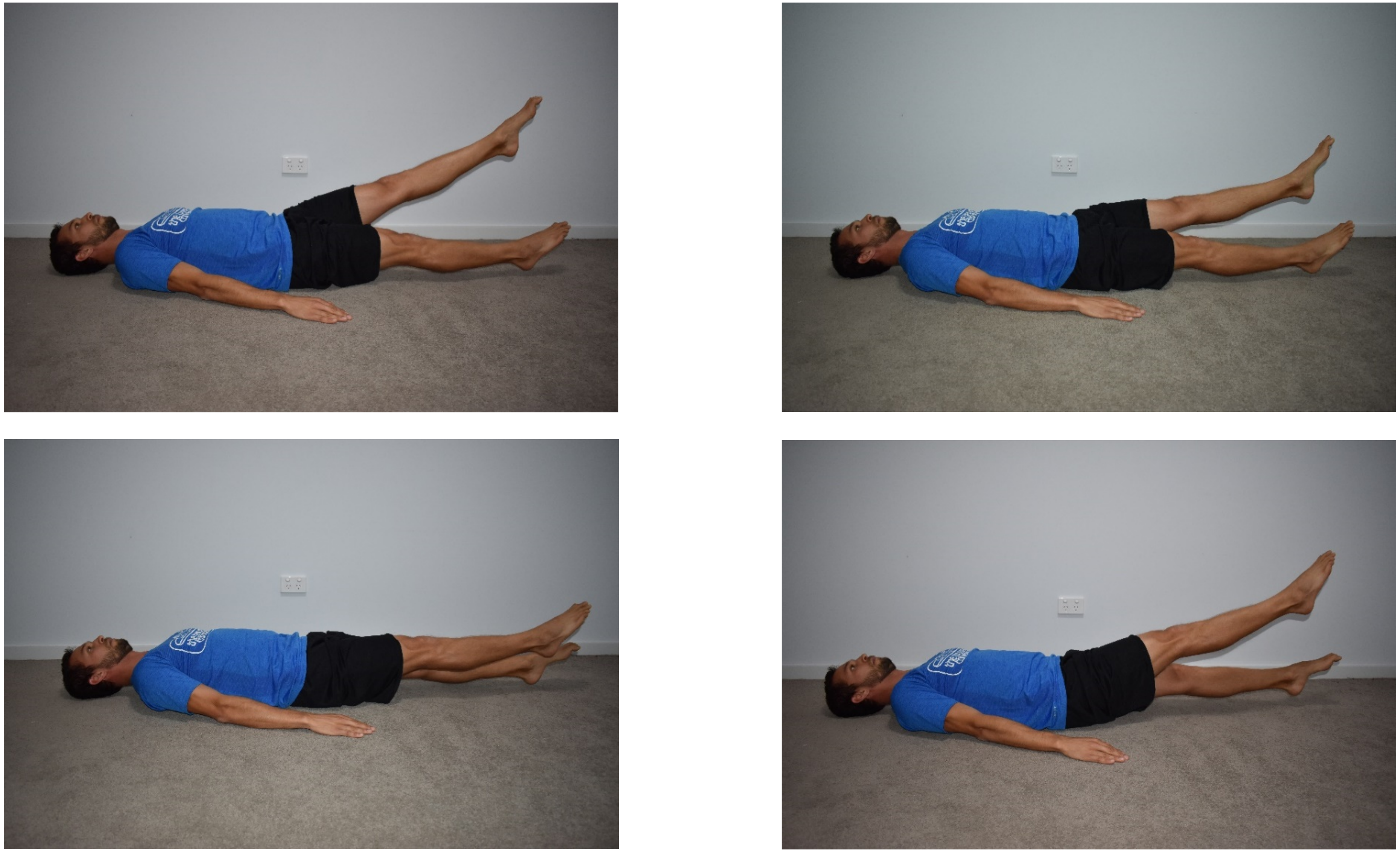

Figure 6-1. **Example of a dry-land strength training exercise that can be used to challenge the torso muscles to control rotation about the longitudinal axis produced by lower limb movements. The swimmer should be instructed to use the torso muscles to prevent the hips, rib cage, and shoulders from moving while alternating the lower limbs through up and down movements in a motion similar to the flutter kick. The sequence of the movement above is top left, top right, bottom left, and bottom right.**

The torso muscles and posture

Exercises designed with a goal of resisting rotation between the upper and lower torso can be used to challenge the torso muscles to maintain a posture that is similar to the prone body position in front crawl swimming. For example, in a plank position (i.e. lying prone and balancing on toes and forearms to suspend the body above the ground), a swimmer can perform alternating arm lifts and leg lifts while keeping the shoulders and hips parallel to the ground. This exercise requires torque from the torso muscles to prevent the pelvis from rotating as the body's base of support changes when an arm or a leg is lifted (Figure 6-2). Other exercises that challenge the torso muscles to resist rotation between the upper and lower torso could include asymmetric pushing and pulling (i.e. moving a load with only one arm). Kritz, Cronin, and Hume (2010) provided examples of pushing and pulling exercises as well as exercise progressions that can be used by coaches to develop dry-land strength training for swimmers.

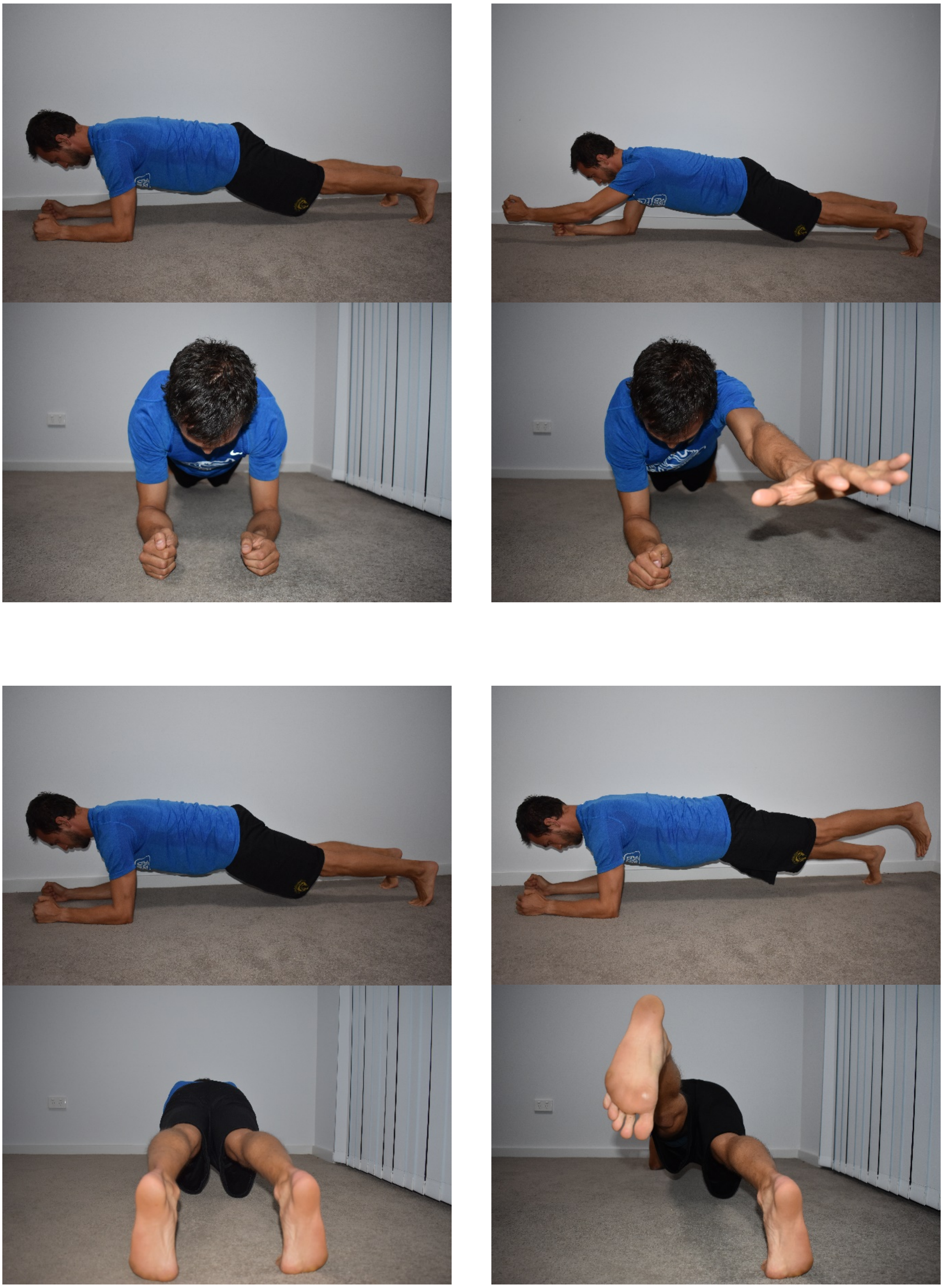

Figure 6-2. Example of an exercise designed to challenge a swimmer to maintain posture in a prone position. From a plank position balancing on both forearms and both feet (left column of pictures), the swimmer should be instructed to keep an imaginary line joining the left and right hip and left and right shoulder parallel to the floor while raising one arm (top right) and one leg (bottom right) at a time.

Limitations and Future Directions

One major limitation of this thesis, which is common to most biomechanical research, was that all of the participants were male. This limits the generalisability of these findings by neglecting the effect of sex on swimming kinematics and torso muscle activity patterns (Rouard & Billat, 1990). It is necessary for future research to be conducted with female participants to provide guidance for the development of dry-land strength training programs that are specific to female front crawl swimmers.

While the selection of one stroke cycle for analysis is common in swimming research, the ability to analyse the effects of one stroke cycle on the next is limited in this approach. This limitation was addressed in each of the studies in this thesis by including multiple trials from each participant at each front crawl pace. Nonetheless, the importance of expanding analyses from just one stroke cycle to multiple consecutive stroke cycles per trial should be considered for future research.

The ability to accurately estimate torques in an aquatic environment is limited by the complexity of fluid dynamics. Several technologies, such as computational fluid dynamics (CFD) (R. C. Cohen, Cleary, Mason, & Pease, 2018), particle image velocimetry (PIV) (Hochstein, Pacholak, Brücker, & Blickhan, 2012), and pressure sensors attached to the hands and feet (Kudo, Yanai, Wilson, Takagi, & Vennell, 2008; Tsunokawa, Nakashima, & Takagi, 2015), can improve estimations of fluid forces during front crawl swimming. One limitation of this thesis was the use of kinematic and EMG data to make conclusions regarding the torques produced in front crawl swimming. Nonetheless, findings from this thesis provide a foundation for future research into the demands on the torso muscles in swimming. Future studies should compare torso muscle activity with estimates of torques during front crawl swimming.

The biomechanical analyses in this thesis were focused on rotation about the body’s longitudinal axis. Torques that swimmers encounter, however, are not restricted to one axis of rotation. The directions in which the external and internal torques are acting have implications when designing training to help swimmers meet the demands of front crawl swimming. Future studies should investigate the association between torso muscle activity and rotation about the transverse axis (i.e. that influences the body’s pitch angle) and sagittal axis (i.e. the body’s yaw angle) to build upon the findings from this thesis. By comparing torso muscle activity with rotation about multiple axes in front crawl swimming, the role of the torso muscles in maintaining posture could be better understood.

The movements of the arms and legs were not quantified in this thesis beyond analysis of angular momentum in Chapter 4 that included both the left and right upper and lower limbs. While the stability from the torso muscles is likely to improve force generation from the limbs (Hodges & Richardson, 1997b; Willardson, 2007), the association between torso muscle activity and limb movements in front crawl swimming is unknown. Patterns of torso muscle activity during different phases of the arm stroke and the flutter kick can be used to verify the stabilising role of the torso muscles proposed in this thesis.

EMG signal drop-out reduced the number of trials that could be included in analyses of muscle activity. The temperature and humidity of the pool deck presented a challenge to ensuring electrodes remained in contact with the skin. The location of the lumbar erector spinae electrodes made these electrodes particularly susceptible to detachment from the skin. EMG electrode preparation was performed in an air-conditioned room, though some participants commented they were warm and had begun to sweat during EMG preparation. Researchers should be aware of these challenges when collecting EMG data in humid environments such as the pool deck and take steps to reducing the impact on data acquisition.

Integrated EMG was chosen to analyse muscle activity over EMG normalised to MVC in Chapter 5 because the participants lacked experience in producing a true maximal effort from the torso muscles. The majority of swimmers from whom EMG data were recorded had never previously taken part in a scientific research project, let alone one that involved EMG. MVC data were recorded from every participant using previously established protocols (McGill et al., 1996); however, muscle activity during swimming trials for most participants was higher than those recorded during the MVC trials. It was therefore deemed more appropriate to analyse integrated EMG instead of EMG normalised to MVC. Prior experience in producing maximal efforts has been shown to influence one's ability to produce a true MVC (Vera-Garcia, Moreside, & McGill, 2010). Participants can also be trained to produce true MVCs (Graves et al., 1990); however, two hours were required to complete the data collection protocol for the study in Chapter 5 and it was not feasible to allocate additional time to train participants to produce reliable MVCs. Indeed, this would have likely increased the number of EMG channels lost during collection from participants sweating. The normalisation of EMG data to MVC would have permitted the comparison of findings from the study in Chapter 5 to future studies of torso muscle activity in swimming. It may be useful, if possible, for future studies of torso muscle activity in swimming to include a training session prior to in-water data collection to ensure true MVCs can be elicited from novice participants.

The EMG equipment and reflective markers used for the study in Chapter 5 may have affected the participants' swimming motions and drag forces they encountered. Care was taken to ensure the EMG cables did not drag through the water or interrupt each participant's stroke. The EMG cables were taped to carabiners that slid along a steel cable above the length of the pool and sufficient slack was left in the EMG cables to ensure they were not under tension. One researcher's sole task during the swimming trials was to pull the carabiners along the length of the pool in a way that kept the EMG cables above the water and out of the swimmer’s way. While the EMG equipment attached to the swimmers (e.g. preamplifiers, electrodes) may have influenced active drag, participants reported they did not feel encumbered while they swam. It would be beneficial for future research to be conducted on the effects of EMG apparatus and reflective markers attached to a swimmer on active drag.

Torso twist in Chapters 3 and 4 were determined as the relative angle between shoulder roll and hip roll, where shoulder roll and hip roll were calculated as the horizontal axis perpendicular to the intended swimming direction and vectors connecting the shoulder and hip joint centres, respectively. In Chapter 5, torso twist was the angle between the thorax and pelvis local coordinate systems about the distal-to-proximal axis of each segment, where the thorax and pelvis were modelled in three dimensions with the aid of optoelectronic cameras. Three-dimensional motion capture technology had been developed over the decade between the time the data in Chapters 3 and 4 were collected by Dr Carla McCabe and her colleagues and the study in Chapter 5. The differences in the motion capture systems used limits direct comparisons of findings between Chapters 3 and 4 and Chapter 5. The improvements in motion capture technology permitted more detailed 3D modelling in Chapter 5 than was possible when Dr McCabe collected data for her thesis. Future research is planned to evaluate the differences between thorax/pelvis rotation and shoulder/hip roll using data collected for Chapter 5 of this thesis.

Three-dimensional motion capture of swimming movements is very labour-intensive. Motion capture systems, such as the one developed by Qualisys AB used in this thesis, have decreased the time to acquire and process motion data of swimming; however, difficulties were encountered. The air-water interface reduced marker visibility due to refraction at the water surface. Normal splashing during front crawl swimming produced a large amount of reflections that made tracking of some of the markers difficult. The precision of the Qualisys system used in Chapter 5 may have been limited by the number of underwater cameras available (n = 6) for data collection; however, this is a difficult barrier to overcome due to the cost of each camera. Despite these challenges, high quality data were collected for the trials that were included in this thesis.

The front crawl stroke can be legally used in twenty-five of the thirty-seven swimming events to be included in the 2020 Summer Olympic Games in Japan (i.e. 50m, 100m, 200m, and 400m freestyle for women and men; 800m freestyle for women and 1500m freestyle for men; 10km open water swim for women and men; 200m and 400m individual medley for women and men; 4x100m and 4x200m freestyle and 4x100m medley relays for women and men; and 4x100m and 4x200m freestyle and 4x100m medley mixed sex relays). Competitive swimmers therefore tend to devote most of their training time to front crawl, even if they specialise in one of the other three competitive strokes (i.e. butterfly, backstroke, and breaststroke) (Stewart & Hopkins, 2000). For this reason, the findings from this thesis are likely to benefit most competitive swimmers. Furthermore, the findings presented here may benefit triathletes who also use the front crawl stroke when racing. While the purpose of this investigation was to provide guidelines for dry-land strength training specific to the front crawl stroke, future research into the demands of the other three competitive strokes is required.

It was assumed that the torso muscles play an important role in front crawl swimming and require conditioning in dry-land training. Though few scientific investigations of the roles of the torso muscles in front crawl exist, coaches and swimmers devote a large portion of dry-land training to condition the torso muscles and this warranted an exploration of the demands on the torso muscles in front crawl. Despite a lack of scientific evidence for the roles of the torso muscles in front crawl, it is hoped the dry-land training guidelines developed in this thesis will provide coaches and swimmers with tools to better prepare athletes for front crawl swimming.

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APPENDIX A:

Information for swimmers for Chapter 5 data collection

(Portuguese)

ESTUDO DA ELECTROMIOGRAFIA DE SUPERFÍCIE DOS MÚSCULOS DO TRONCO EM DUAS VELOCIDADES DE NATAÇÃO DIFERENTES

INFORMAÇÃO PARA OS NADADORES

Pré teste:

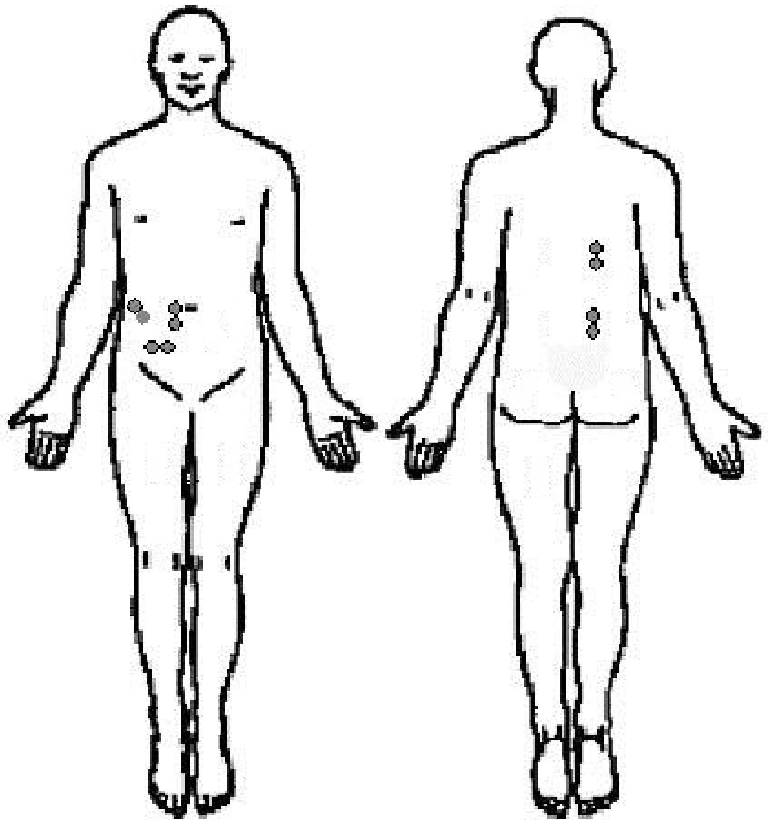
- Traga 1 fato de banho slip.
- Traga 2 toalhas (uma microfibra, se tiver, e outra normal).
- Traga o blusão e calça curta do fato de treino do clube.
- Traga chinelos e calçado esportivo.
- Traga óculos e touca de natação de competição.

Instruções:

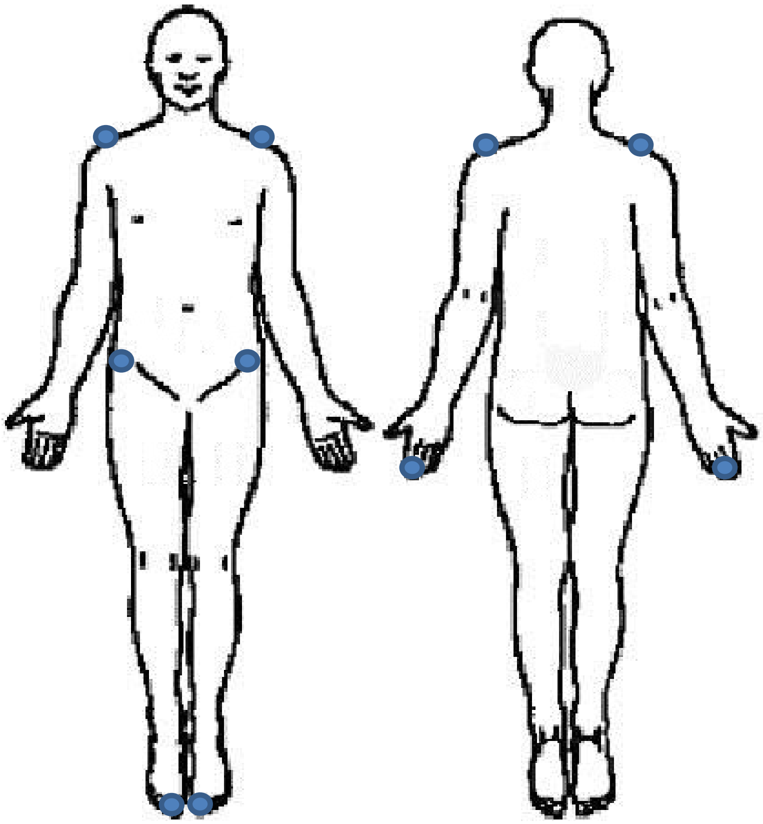
- Venha à prova de carro ou a pé (se vier de bicicleta, faça isso devagar).
- Evite o consumo de medicamentos, café e chá nas 12 horas anteriores ao teste.
- Não realize exercícios físicos intensos nas 12 horas anteriores ao teste.
- Coma pelo menos 2 horas antes do teste, mas não coma abundantemente.
- Evite tratamentos terapêuticos ou exposição excessiva a UV 24 horas antes do teste.
- Evite o uso de produtos cosméticos nas pernas (cremes, óleos, sprays ...) antes do teste.

Desenvolvimento do teste:

- Ao chegar na piscina, o nadador deve colocar o fato de banho para realizar o sessão de trenamento.
- Serão tomadas medidas antropométricas (peso e altura).
- Realização de um aquecimento personalizado de 1000 m de volume (<30 minutos).
- O equipamento de eletromiografia será anexada à pele por um assistente de pesquisa por cima de três músculos do abdômen e dois músculos das costas para o lado direito mostrado na figura abaixo.
- Depois disso, o nadador deve realizar contração máxima dos músculos do tronco contra a resistência de um assistente de pesquisa na posição sentada.
- Marcadores reflexivos também se prenderão à pele acima dos ossos do quadril, no topo dos ombros, no terceiro dedo de cada mão e no dedão do pé mostrado na figura abaixo.
- O nadador ficará em pé no meio da piscina, onde os movimentos de natação serão registrados durante os testes. Um quadro de calibração será gravado para ajudar a identificar os marcadores reflexivos.
- O nadador realizará 4x25m no ritmo do sprint (ou seja, o mais rápido possível) e 4x25m no ritmo de 400m. A ordem dos testes será atribuída aleatoriamente. Entre cada teste de 25m, o nadador deve retornar à parede inicial no ritmo de recuperação e descansar por 2 minutos antes de iniciar o próximo teste.



Colocação de electrodos.



Colocação de marcadores

APPENDIX B:

Consent form for Chapter 5 data collection (Portuguese)

LABORATÓRIO DE BIOMECÂNICA DO PORTO
U.PORTO

U.PORTO
FACULDADE DE DESPORTO
UNIVERSIDADE DO PORTO

DECLARAÇÃO DE CONSENTIMENTO INFORMADO

Estudo da eletromiografia de superfície dos músculos do tronco em duas velocidades de natação diferentes

INFORMAÇÃO

O laboratório de biomecânica do Porto (LABIOMEP-UP), juntamente com a Faculdade de Desporto (FADEUP) da Universidade do Porto, está desenvolveu um projeto projetado para melhorar a compreensão dos requisitos dos músculos do tronco em sprint e 400m livres.

O estudo incluirá 4x25m nos testes de sprint e 4x25m nos testes de uma corrida de 400m, depois um aquecimento personalizado de 1000m. Para medir a atividade muscular durante cada repetição, os eletrodos serão colocados na pele acima de três músculos do abdômen e dois músculos das costas para o lado direito. Os eletrodos não emitem corrente. Eles medem a quantidade de energia elétrica enviada pelo cérebro para contrair os músculos usando eletromiografia. Os elétrodos serão colados à pele com um adesivo macio e impermeável para evitar que se movam durante os testes de sprint e de 400m. Os nadadores serão então solicitado a contrair seus músculos abdominais e dorsais contra a resistência de um assistente de pesquisa na posição sentada. Isso nos permitirá determinar a atividade máxima que seu cérebro pode dar seus músculos para padronizar as medições de eletromiografia durante cada teste.

Marcadores reflexivos também se prenderão à pele acima dos ossos do quadril, no topo dos ombros, no terceiro dedo de cada mão e no dedão de pé. Câmaras infravermelhas especializadas capturarão os movimentos dos quadris, dos ombros e dos mãos durante cada teste. Um vídeo será levado para permitir a identificação dos movimentos de cada teste.

Todos os testes serão realizados na piscina da FADEUP localizada na Rua Dr. Plácido da Costa 91, 4200-450 Porto. O tempo estimado para cada sessão de teste será de aproximadamente 90 minutos.

RISCOS

Os nadadores realizarão um aquecimento de 1000m seguido por quatro testes de 25m livres à velocidade máxima com elevada exigência física e quatro testes de 25m livres à velocidade de uma corrida de 400m com exigência física moderada. Isso protocolo é semelhante a uma sessão de treinamento típica.

CONFIDENCIALIDADE

Os dados pessoais decorrentes deste projeto serão tratados seguindo os princípios de confidencialidade de acordo com a Declaração de Helsínquia. Em nenhum dos relatórios do estudo aparecerá o seu nome e a sua identidade não será divulgada a nenhuma pessoa, exceto para cumprir os propósitos do estudo e no caso de emergência médica ou requisito legal. Os dados pessoais dos participantes serão recolhidos no estudo, mas não serão publicados em nenhum relatório, ou artigo. Os dados serão confidenciais e serão controlados exclusivamente por membros da equipa de pesquisa.

CONTACTO

Para quaisquer perguntas relacionadas com o estudo, problemas no teste, mudança de marcação, etc., pode ligar para +34 695629849 e falar com a Dra. Irene Jiménez, ou pelo telefone +34 676635332 com a Dra. Marina Gil (equipe de pesquisa do LABIOMEP).

PARTICIPAÇÃO

A sua participação neste estudo é voluntária e, portanto, pode comunicar a qualquer momento o seu desejo de não continuar.

CONSENTIMENTO

Depois de ler este documento, declaro que as condições expostas são satisfatórias, que me explicaram os testes com clareza e responderam às minhas dúvidas. Mais declaro a minha disposição para participar voluntariamente no estudo.

Porto, em ____ de _______________ de 2018

Assinado o participante (Pai ou tutor legal):

Sr/Sra.:_______________________________________

Documento de Identificação:____________________

Assinado o responsável pelo projeto:

(Prof. Doutor J. Paulo Vilas-Boas)

Documento de

Identificação:_3843793_______________

APPENDIX C1-C12:

Protocols for Chapter 5 data collection

Research assistants were divided into teams with two members in each. EMG1 and EMG2 were responsible for tasks related to electromyography. QUAL1 and QUAL2 were responsible for tasks related to motion capture. The tasks performed by the author of this thesis are also listed.

APPENDIX C1: Set up

Electromyography	**Responsible**	**Qualisys**	**Responsible**
Turn on: - BioPac - Computer	Jordan		
AcqKnowledge Set Up: - Adjust acquisition settings	Jordan		
Lay out EMG equipment: - 2 razors - 1 alcohol bottle - 1 alcohol pad bag - 20 EMG electrodes with rubber gaskets - 1 Ground EMG leads - 4 Regular EMG leads - 2 scissors - 2 rolls of hockey tape - 1 box of Diamond FlexFix - 1 roll of Large FlexFix - 2 rolls of electrical tape Pass EMG cables through back of FastSkin Lay out Qualisys equipment: - 3 thoracic clusters - 1 pelvis cluster - 8 shoulder roll markers - 8 hip markers - 10 hand markers - 10 foot markers	EMG1 EMG2	Put calibration frame in pool Above water calibration Below water calibration Dual media calibration	Qual1 Qual2 Jordan

APPENDIX C2: Anthropometrics

Task	Equipment	Responsible
Height		
Participant stands with feet flat as close to the wall as possible (i.e. heels, buttocks, and thorax touching wall). Participant looks directly forward. Arms are relaxed to the side.	Height measurer	Qual2
Researcher lowers scale to the top of participant’s head		Qual2
Body Mass		
Participant stands on scale looking directly forward	Scale	Qual2
Dominant Limb		
Writing, throwing, swinging (e.g. golf, baseball, etc.)		Qual2
Breathing Side		
Preferred breathing side while swimming freestyle		Qual2
50m PB		
Short AND long course, in the past 12 months		Qual2
400m PB		
Short AND long course, in the past 12 months		Qual2
Best crawl event		
E.g. Best FINA time		Qual2

APPENDIX C3: Warm up shown to participants in Portuguese

AQUECIMENTO
Total: 1000m

200m crol

300m p/ ordem:
- 25m normal
- 25m drill
- 25m normal

4x50m crol @ 60s:
- 50m composto
- 50m forte
- 50m rápido sem parede
- 50m RÁPIDO

50m calmo

4x50m crol @ 60s, ritmo de 400m

50m calmo

APPENDIX C4: Warm up in English

WARM UP
Total: 1000m

200m freestyle

300m IM order:
- 25m swim
- 25m drill
- 25m swim

4x50m freestyle @ 60s:
- 50m build
- 50m strong
- 50m fast off walls
- 50m FAST

50m easy

4x50m freestyle @ 60s, 400m pace

50m easy

APPENDIX C5: EMG and Qualisys preparation

Electrode purpose	**Location**
Internal obliquus	Diagonally, medial to linea semilunaris and superior to inguinal ligament at level of ASIS
External obliquus	Diagonally, 3cm lateral to linea semilunaris at level of umbilical (lateral electrode superior)
Rectus abdominis	Vertically, 3cm lateral to umbilicus
Lower erector spinae	Vertically, 3cm lateral to spine at L3 (at level of iliac crest)
Upper erector spinae	Vertically, 5cm lateral to spine at T9 (counting up from T12)
Reference	Right PSIS

Qualisys Marker Location	**Qualisys Marker Location**
Thorax 1. Left acromion 2. Right acromion 3. Left clavicle (medial-lateral junction) 4. Right clavicle (medial-lateral junction) 5. Left lateral 10th rib 6. Right lateral 10th rib Clusters a. Sternum b. T-spine	Pelvis 1. Left ASIS 2. Right ASIS 3. Left iliac spine 4. Right iliac spine 5. Left greater trochanter 6. Right greater trochanter Clusters a. Sacrum
Location	**Location**
Left and Right Hand Entry - *Distal 3rd phalanx (tape)* 1. Head of 5th metacarpal 2. Radial styloid process 3. Ulnar styloid process	Left and Right Foot Speed - *Distal 1st phalanx (tape)* 1. Head of 5th metatarsal 2. Medial malleolus 3. Lateral malleolus
1. Medial knee 2. Lateral knee	1. Medial elbow 2. Lateral elbow
Magnetic Markers: 16 **Normal Markers: 12** **Clusters: 3 = 9 magnetic markers**	

EMG	Equipment	Responsible	Qualisys	Equipment	Responsible
Dry participant	Towel	EMG1: Abdo EMG2: Back			
Mark all EMG electrode placement sites with pen	Pen	Jordan			
Shave skin	Razor	EMG1: Abdo EMG2: Back	Mark torso landmarks	Pen	Jordan
Clean with alcohol	Alcohol Cotton	EMG1: Abdo EMG2: Back	Attach magnetic coins to torso		Qual1: Shoulders Qual2: Hips
Attach electrodes to placement sites	EMG electrodes	Jordan	Cover coins and normal markers with FlexFix		Qual1: Shoulders Qual2: Hips
Connect EMG lead to electrodes and tape pre-amp to skin - Abdo: cables running in lateral direction - Back: cables running in inferior direction	EMG leads Hockey tape	EMG1: Abdo EMG2: Back Jordan	Attach clusters		Jordan
Check EMG signals		Jordan			
Place “LARGE FlexFix” over entire EMG complex	Opsite FlexFix	EMG1: Abdo EMG2: Back			
Create umbilical with EMG cables	Electrical tape				
Participant puts on FastSkin	FastSkin				
Check EMG signals		Jordan			

APPENDIX C6: Static calibration and swimming trials

STATIC CALIBRATION

Task	Equipment	Responsible
Calibration process explained to participant		Qual1
Participant stands on platform and rotates slowly		Qual1 Qual2
Confirmation that trigger from Qualisys to BioPac is working		Jordan

SWIMMING TRIALS

Task	Equipment	Responsible
Start GoPro1 and GoPro2		EMG1 EMG2
Manage EMG cable harness		EMG1 EMG2
4x25m @ 400m Pace		
START TRIAL		
Participant pushes from starting wall and swims	Stop watch	Jordan
Participant stops at 20m barricade		
STOP TRIAL		
Participant returns to starting wall at recovery pace		
Participant rests for an additional 2min		Jordan
All markers verified		Swimmer
5min rest in pool		
4x25m @ Sprint Pace		
Repeat protocol at Sprint Pace		

APPENDIX C7: Swimming protocol for participants in Portuguese

PROTOCOLO DE NATAÇÃO

Velocidade	Teste	Actvidade
400m	Teste 1	25m no velocidade de 400m 25m no velocidade recuperação 2min de descanso
	Teste 2	25m no velocidade de 400m 25m no velocidade recuperação 2min de descanso
	Teste 3	25m no velocidade de 400m 25m no velocidade recuperação 2min de descanso
	Teste 4	25m no velocidade de 400m 25m no velocidade recuperação
5min de descanso		
Sprint	Teste 1	25m no velocidade máximo 25m no velocidade recuperação 2min de descanso
	Teste 2	25m no velocidade máximo 25m no velocidade recuperação 2min de descanso
	Teste 3	25m no velocidade máximo 25m no velocidade recuperação 2min de descanso
	Teste 4	25m no velocidade máximo 25m no velocidade recuperação

APPENDIX C8: Swimming protocol for participants in English

SWIMMING PROTOCOL

Pace	Trial	Task
400m	Trial 1	25m at 400m pace 25m active recovery 2min rest
	Trial 2	25m at 400m pace 25m active recovery 2min rest
	Trial 3	25m at 400m pace 25m active recovery 2min rest
	Trial 4	25m at 400m pace 25m active recovery
5min rest		
Sprint	Trial 1	25m at maximum speed 25m active recovery 2min rest
	Trial 2	25m at maximum speed 25m active recovery 2min rest
	Trial 3	25m at maximum speed 25m active recovery 2min rest
	Trial 4	25m at maximum speed 25m active recovery

APPENDIX C9: Post collection

Task	Equipment	Responsible
Remove EMG and Qualisys equipment		EMG2 Qual2
Put Data Collection Sheet in folder		Qual1
Put Qualisys data on USB		Qual1
Put EMG data on USB		Jordan
Bring water GoPro1 and GoPro2 to class room		EMG1
Put data on Jordan’s computer - GoPro1 - GoPro2 - EMG data - Qualisys data		Jordan

APPENDIX C10: Data collection timeline

Elapsed Time	Time (min)	Task	Equipment
		SET UP	
0:30	0:30	Set up Protocol	
		PARTICIPANT ARRIVES	
0:00	0:05	Participant reads and signs consent form Protocol explained to participant	Consent Form
0:05	0:05	Participant anthropometrics	Data collection sheet
0:10	0:25	Warm up	
0:35	0:20	EMG and Qualisys prep	EMG kit Qualisys kit
0:55	0:05	MVCs	Data collection sheet
1:00	0:05	Reference movements recorded	Data collection sheet
1:05	0:02	Magnetic markers added EMG cables secured in harness	Qualisys kit
		Participant enters pool	

		Quiet lying recorded
1:07	0:03	Qualisys calibration
		4x25m @ **400m Pace**
1:10	0:01	Trial 1
1:11	0:02	2min rest
1:13	0:01	Trial 2
1:14	0:02	2min rest
1:16	0:01	Trial 3
1:17	0:02	2min rest
1:19	0:01	Trial 4
1:20	0:05	5min rest between swimming paces
		4x25m @ **Sprint Pace**
1:25	0:01	Trial 1
1:26	0:02	2min rest
1:28	0:01	Trial 2
1:29	0:02	2min rest
1:31	0:01	Trial 3
1:32	0:02	2min rest
1:34	0:01	Trial 4
1:35	0:15	Remove equipment
1:50		FINISHED

APPENDIX C11: Data collection sheet

Consent: ☐		Subject ID:
DOB: Y Y Y Y – M M – D D		Today: Y Y Y Y – M M – D D
Height:	Arm:	Body Mass:
Dominant Limb: R L		Breathing Side: R L
50m short course PB: *within last 12 months		400m short course PB: *within last 12 months
50m long course PB: *within last 12 months		400m long course PB: *within last 12 months
Best crawl event:		

FT1 cal	Zero1:	CalA1:	CalB1:	
FT2 cal	Zero2:	CalA2:	CalB1:	
4x50m @ 60s				
Photos:	EMG and markers (full body) ☐	EMG (electrode) ☐		

EMG sample rate:		Camera sample rate:	
Box 1	Muscle	Box 2	Muscle
Channel 1	IO	Channel 5	LES
Channel 2	EO	Channel 6	UES
Channel 3	RA	Channel 7	
Channel 4		Channel 8	

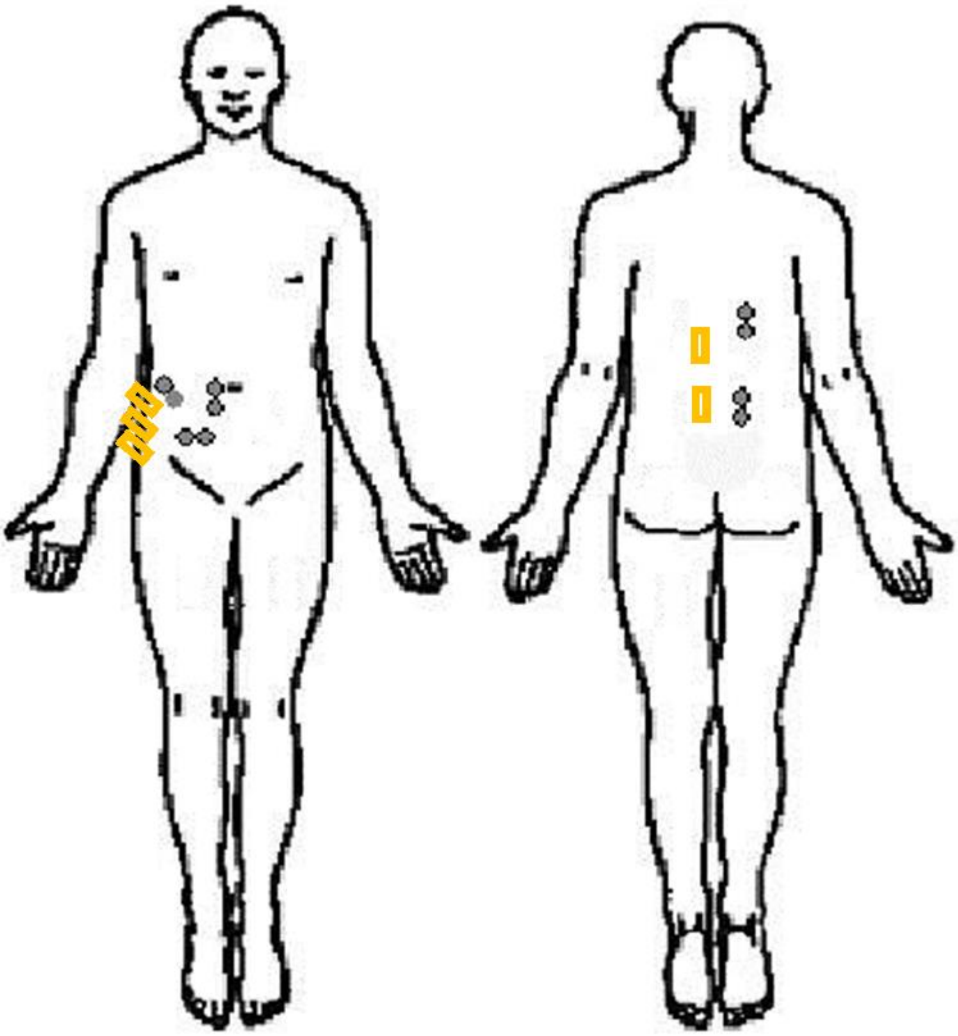
AcqKnowledge	Description		Trial/Comments
MVC_	Prone:	trunk extension right twist left twist	
MVC_	Semi-sitting:	trunk flexion right twist left twist	
Ref_1_	Self-selected		
Ref_2_	Max		
Ref_3_	50%		
QuietLying_	Face-down in water		

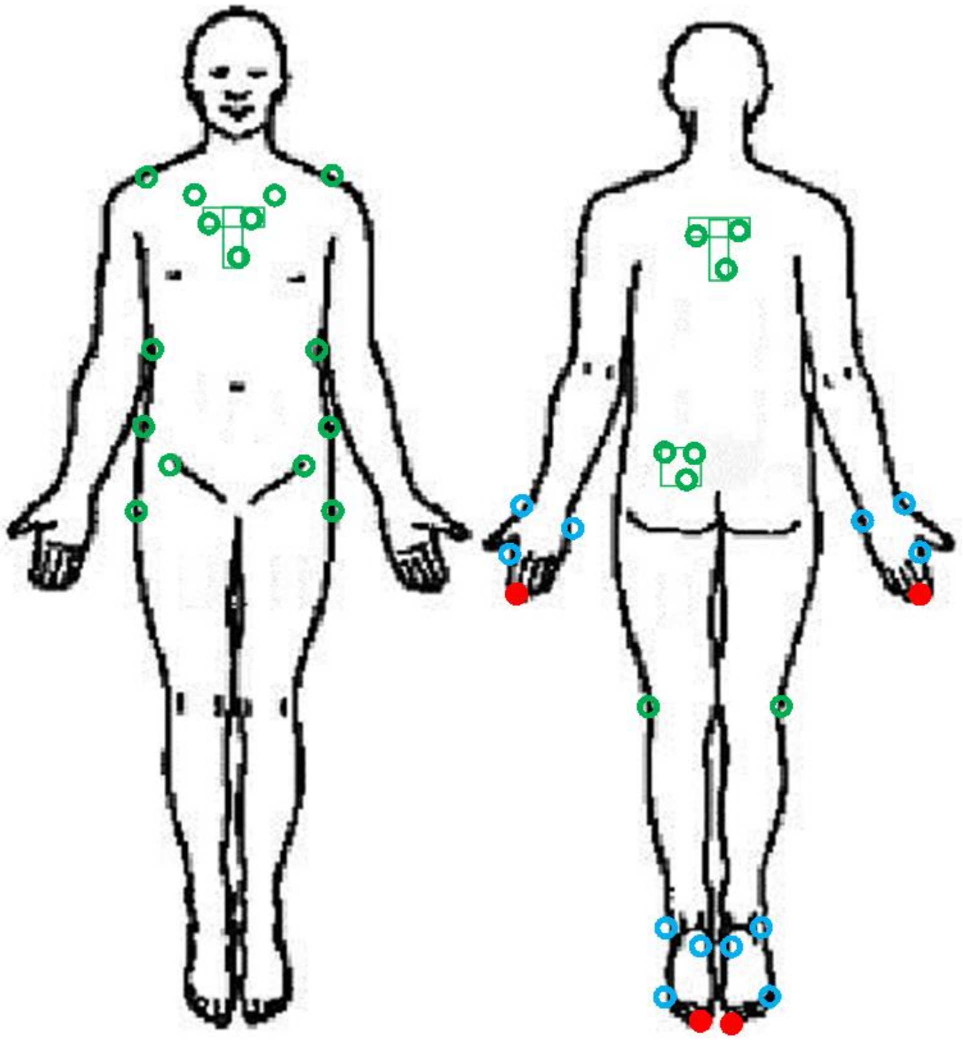
Trial Information

File Name	Comments
400m_T1	
400m_T2	
400m_T3	
400m_T4	
Sprint_T1	
Sprint_T2	
Sprint_T3	
Sprint_T4	

APPENDIX C12: EMG and Qualysis marker placement

Grey dots show approximate location of EMG electrodes and yellow squares indicate approximate locations of pre-amplifiers. Green circles represent locations of magnetic markers and rigid bodies, blue circles are non-magnetic markers, and red dots are the tips of the distal phalanx of the third digit on the hand and distal phalanx of the first digit on the foot.





APPENDIX D:

Visual 3D Commands

Pelvis segment was named “Hips” because Visual 3D contains pre-set segment parameters for “Pelvis”.

```
        ! Fourth order low-pass Butterworth filter with a 6 Hz cutoff
Lowpass_Filter
/SIGNAL_TYPES=TARGET
/SIGNAL_FOLDER=PROCESSED
! /SIGNAL_NAMES=
! /RESULT_FOLDER=PROCESSED
! /RESULT_SUFFIX=
! /FILTER_CLASS=BUTTERWORTH
! /FREQUENCY_CUTOFF=6.0
/NUM_REFLECTED=30
! /NUM_EXTRAPOLATED=0
! /TOTAL_BUFFER_SIZE=6
! /NUM_BIDIRECTIONAL_PASSES=1
;

Recalc
;

        ! Calculate thorax angle, resolved in global coordinate system
Compute_Model_Based_Data
/RESULT_NAME=Thorax_angle
/FUNCTION=JOINT_ANGLE
/SEGMENT=Thorax
/REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=LAB
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
! /TREADMILL_DATA=FALSE
! /TREADMILL_DIRECTION=UNIT_VECTOR(0,1,0)
! /TREADMILL_SPEED=0.0
;

        ! Calculate pelvis angle, resolved in global coordinate system
Compute_Model_Based_Data
/RESULT_NAME=Pelvis_angle
/FUNCTION=JOINT_ANGLE
/SEGMENT=Hips
/REFERENCE_SEGMENT=LAB
/RESOLUTION_COORDINATE_SYSTEM=LAB
```

```
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
! /TREADMILL_DATA=FALSE
! /TREADMILL_DIRECTION=UNIT_VECTOR(0,1,0)
! /TREADMILL_SPEED=0.0
;

        ! Calculate torso twist angle between thorax and pelvis, resolved in pelvis coordinate system
Compute_Model_Based_Data
/RESULT_NAME=Twist_angle_wrtThorax
/FUNCTION=JOINT_ANGLE
/SEGMENT=Thorax
/REFERENCE_SEGMENT=Hips
/RESOLUTION_COORDINATE_SYSTEM=Hips
! /USE_CARDAN_SEQUENCE=FALSE
! /NORMALIZATION=FALSE
! /NORMALIZATION_METHOD=
! /NORMALIZATION_METRIC=
! /NEGATEX=FALSE
! /NEGATEY=FALSE
! /NEGATEZ=FALSE
! /AXIS1=X
! /AXIS2=Y
! /AXIS3=Z
! /TREADMILL_DATA=FALSE
! /TREADMILL_DIRECTION=UNIT_VECTOR(0,1,0)
! /TREADMILL_SPEED=0.0
;
```

APPENDIX E:

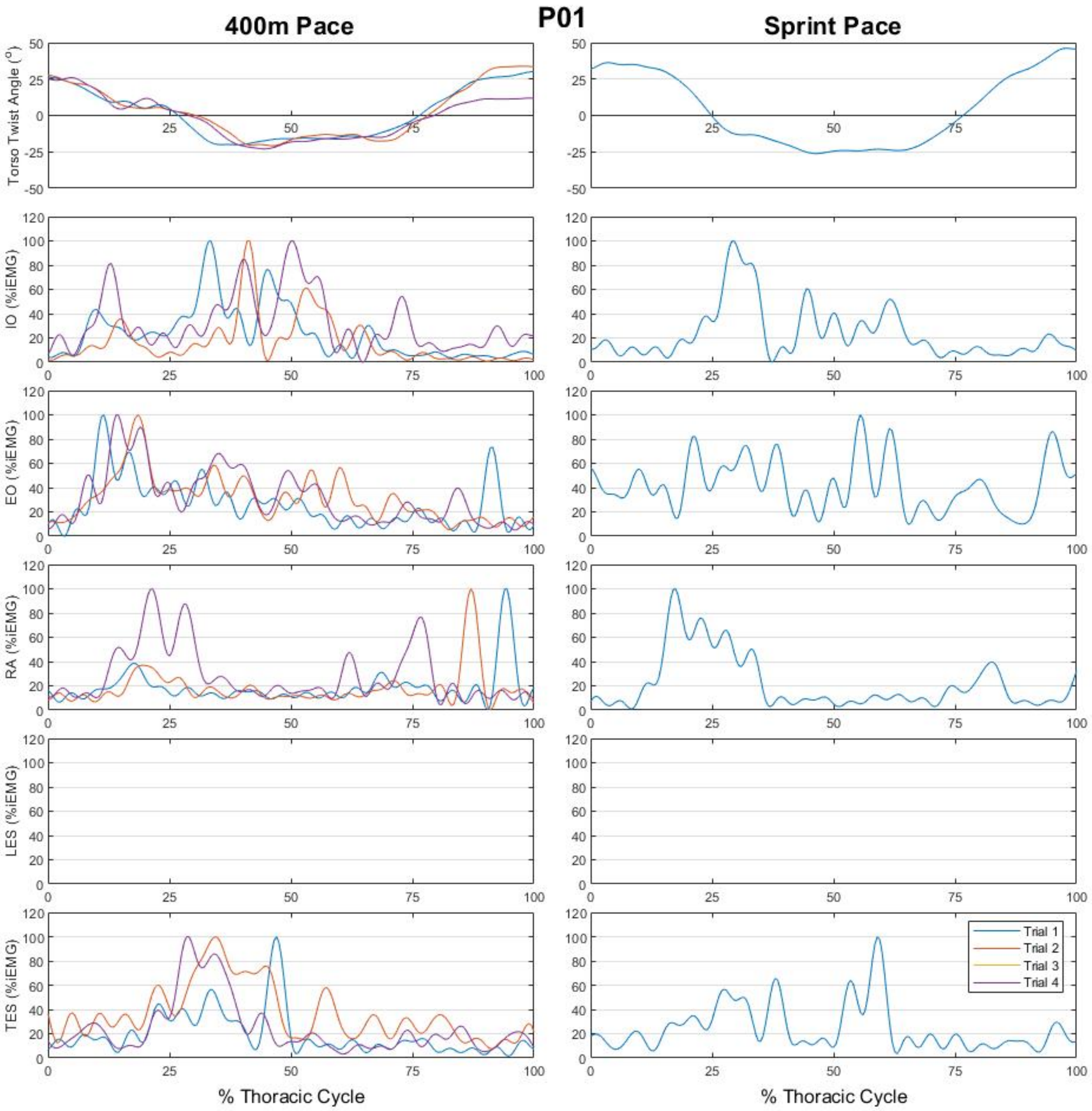
Trials containing thorax and torso twist data for an entire thoracic cycle

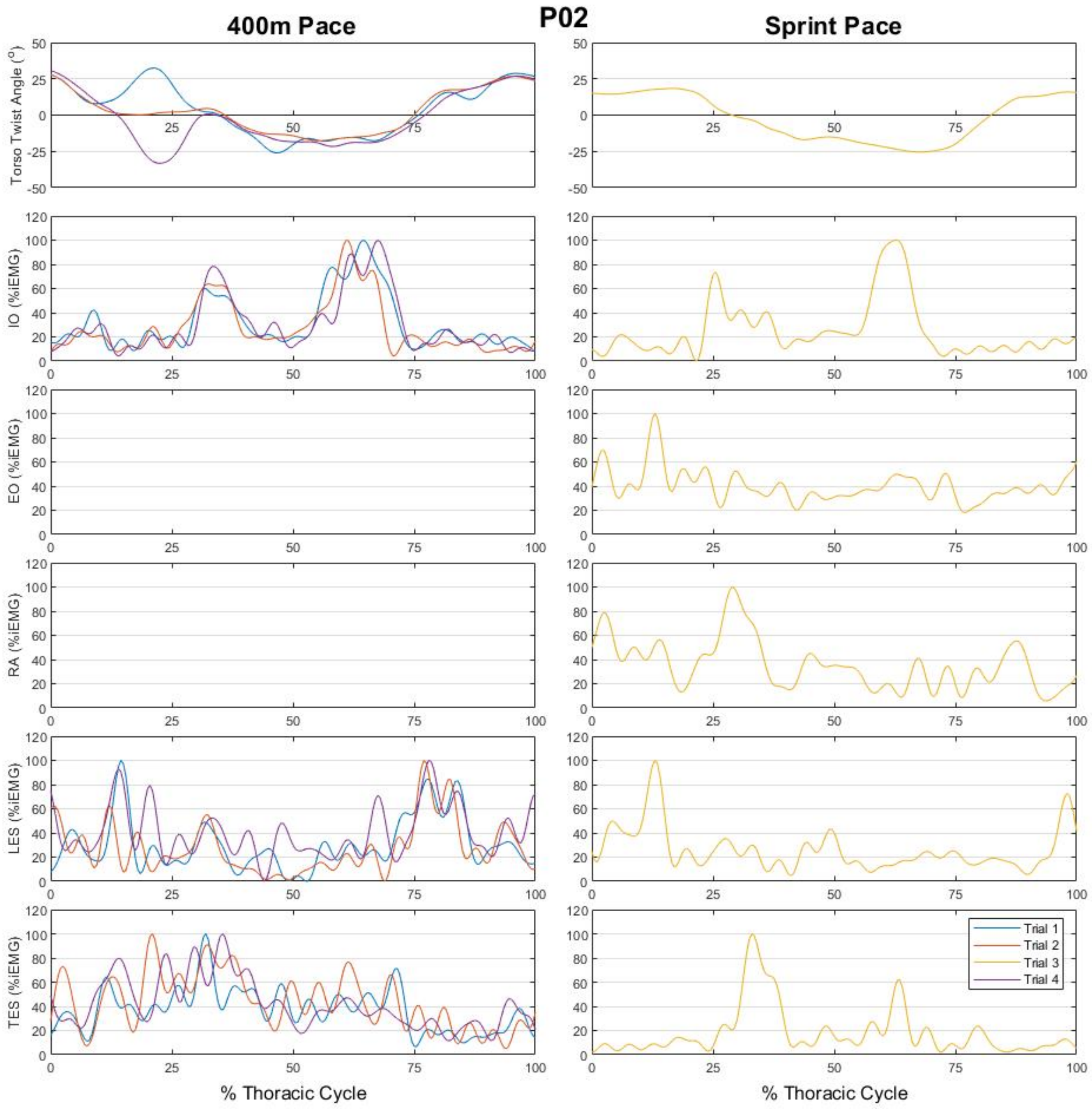
Participant	400m Pace		Sprint Pace	
	Number of trials with Thorax visible for one complete thoracic cycle	Number of trials in which Torso Twist could be calculated for one complete thoracic cycle	Number of trials with Thorax visible for one complete thoracic cycle	Number of trials in which Torso Twist could be calculated for one complete thoracic cycle
S04	4	3	1	1
S05	4	3	2	1
S08	4	3	4	1
S09	2	2	2	1
S10	2	1	4	2
S11	2	1	3	0*
S12	4	1	4	0*
S13	3	3	3	1
S14	2	1	2	0*
S15	4	4	4	3
S16	3	1	2	1
S17	3	2	3	2
S18	4	3	4	4
S19	3	1	4	1
S21	4	2	4	3

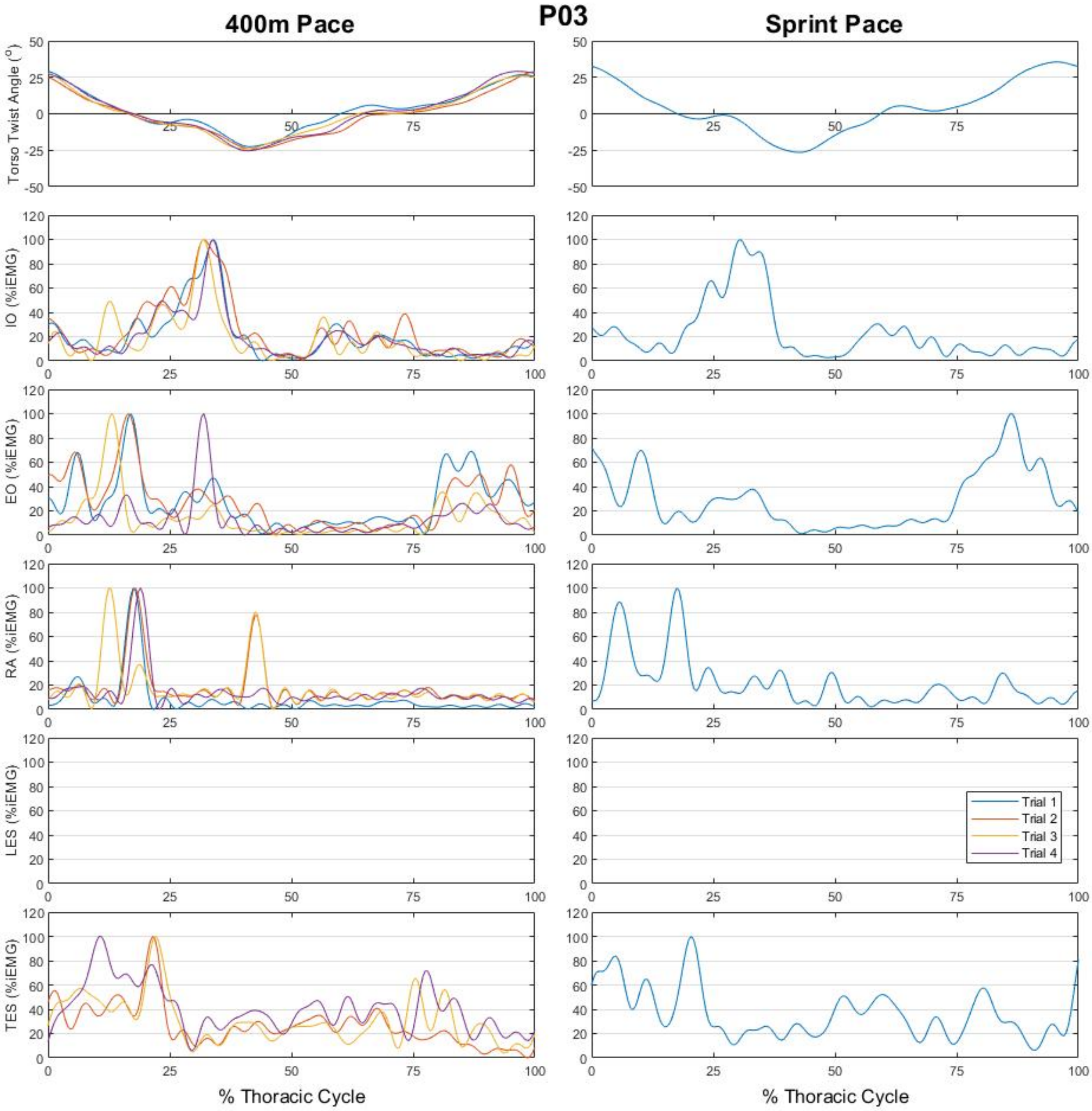
*Torso twist could not be calculated for any trial from S11, S12, and S14 at sprint pace because fewer than three pelvis markers were visible for the duration of an entire thoracic cycle.

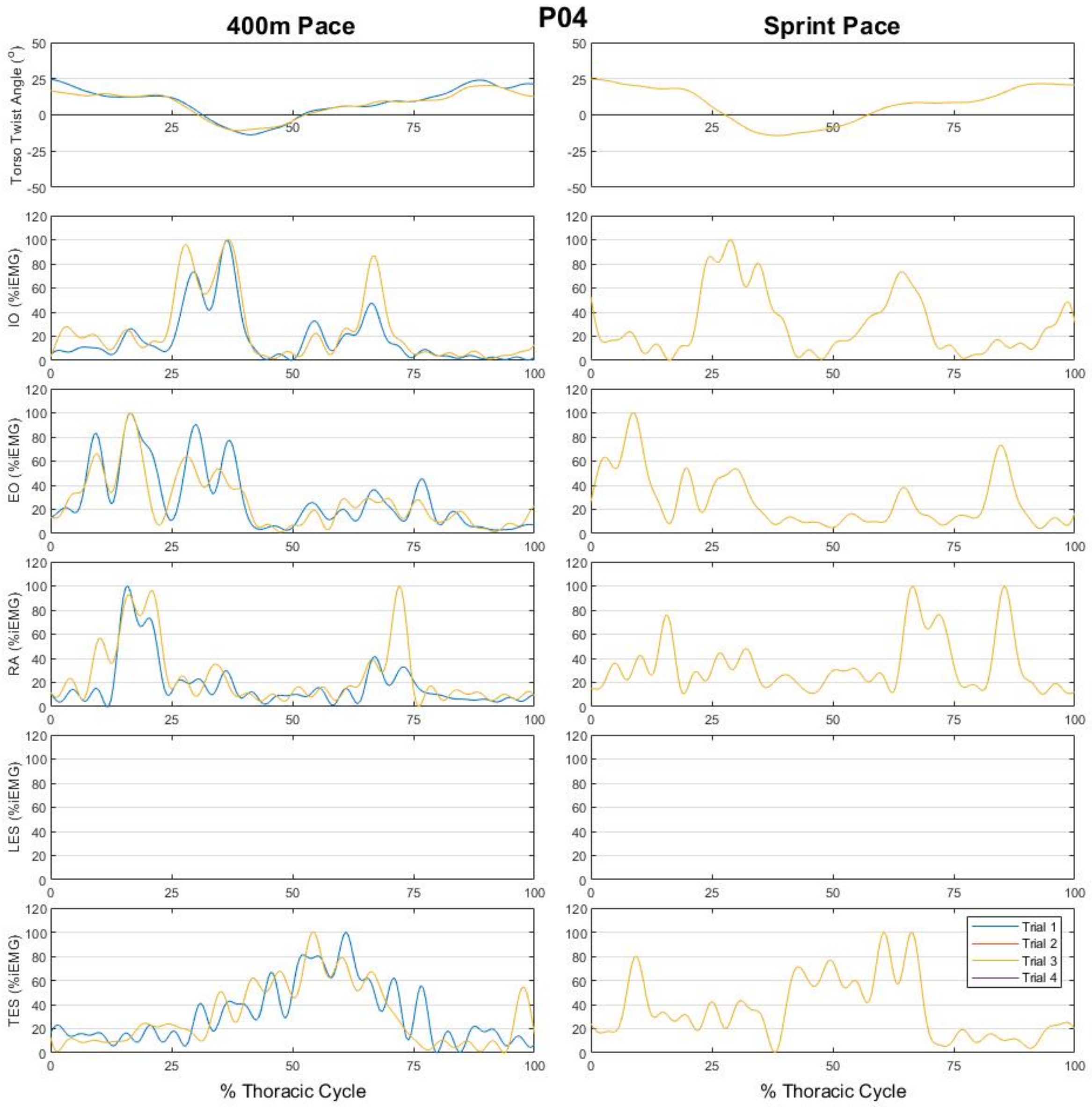
APPENDIX F:

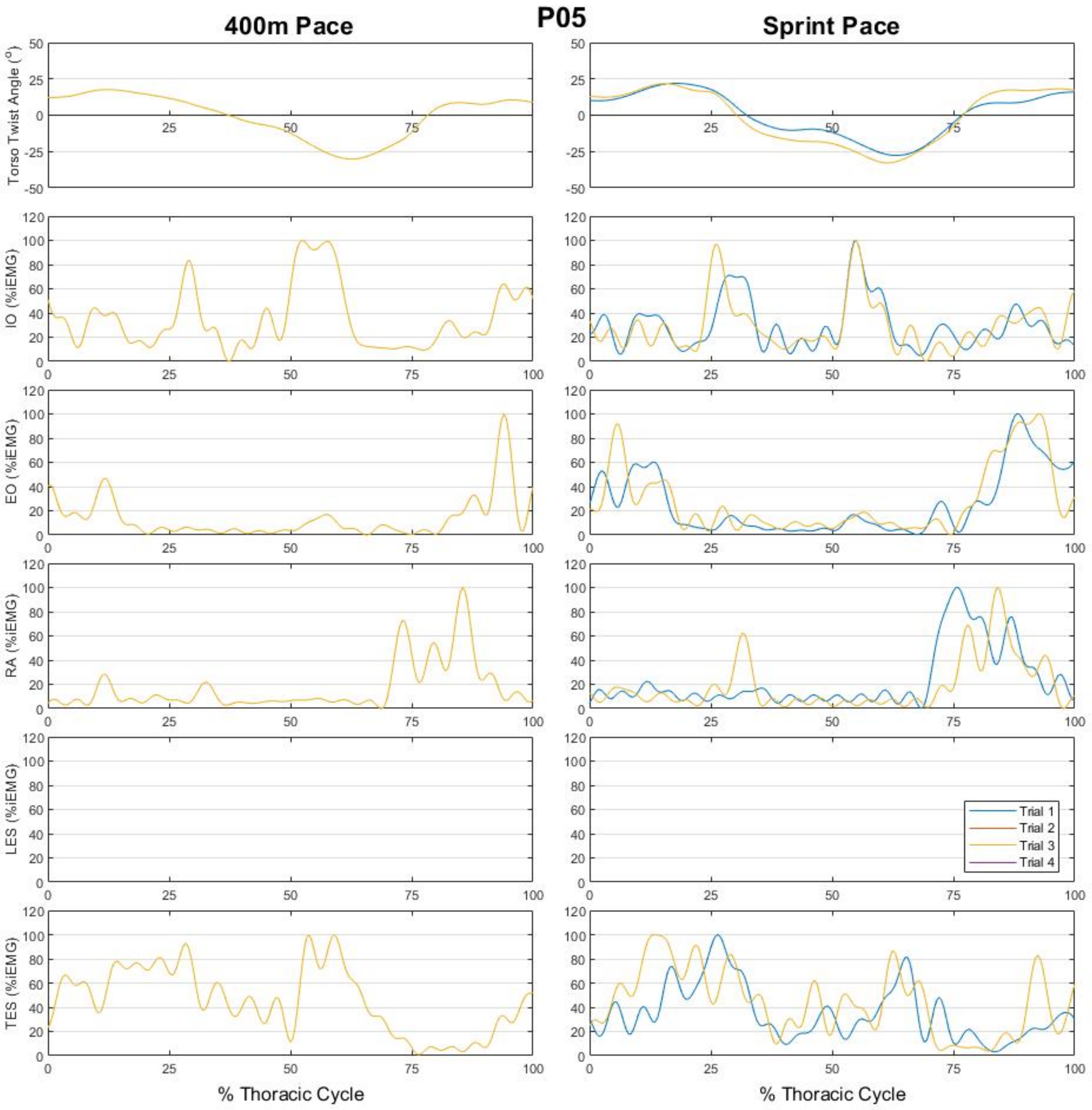
Time series graphs of torso twist angle and torso muscle activity data in trials that contained torso twist data from all participants analysed in Chapter 5

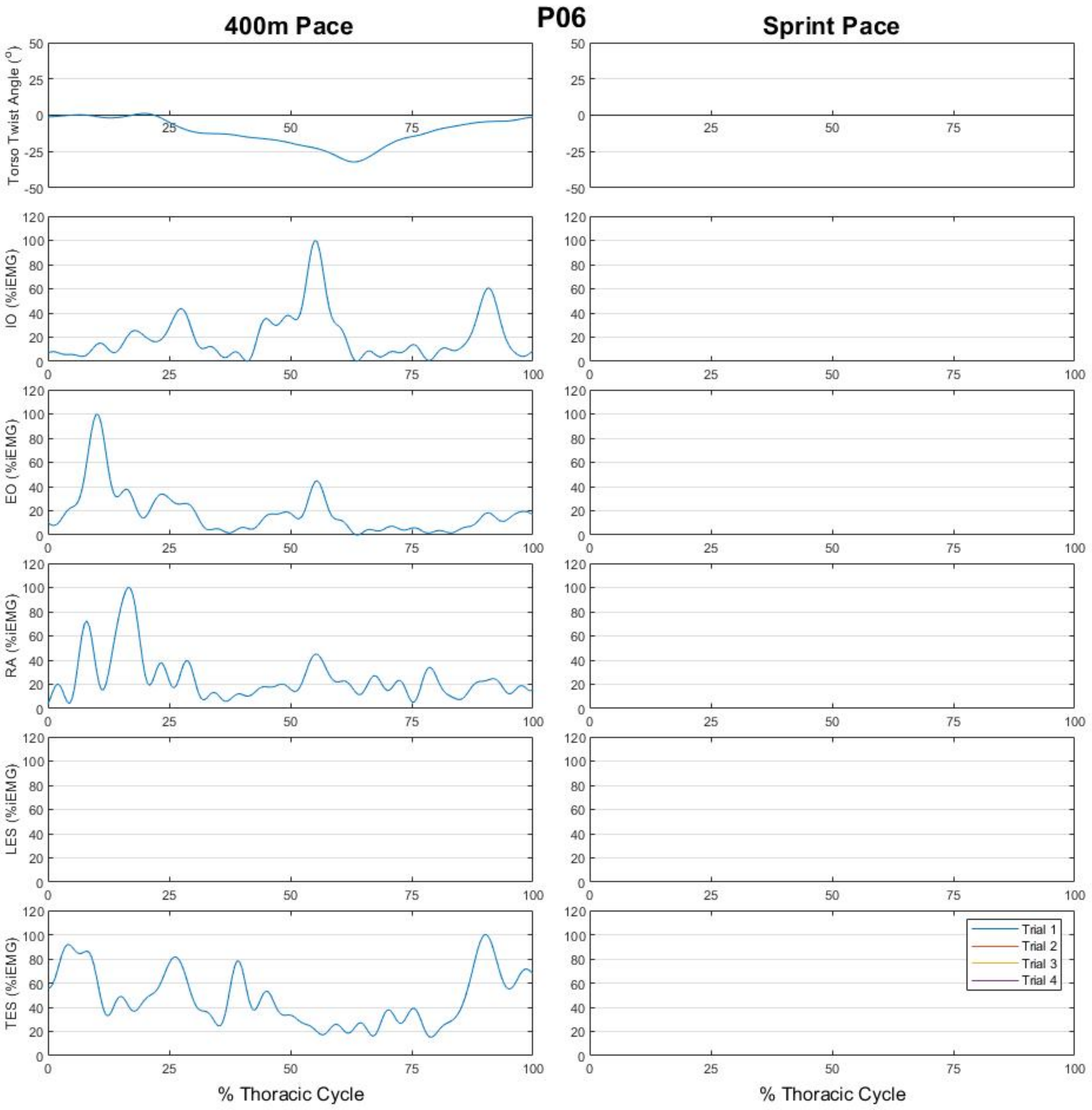

P01
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4

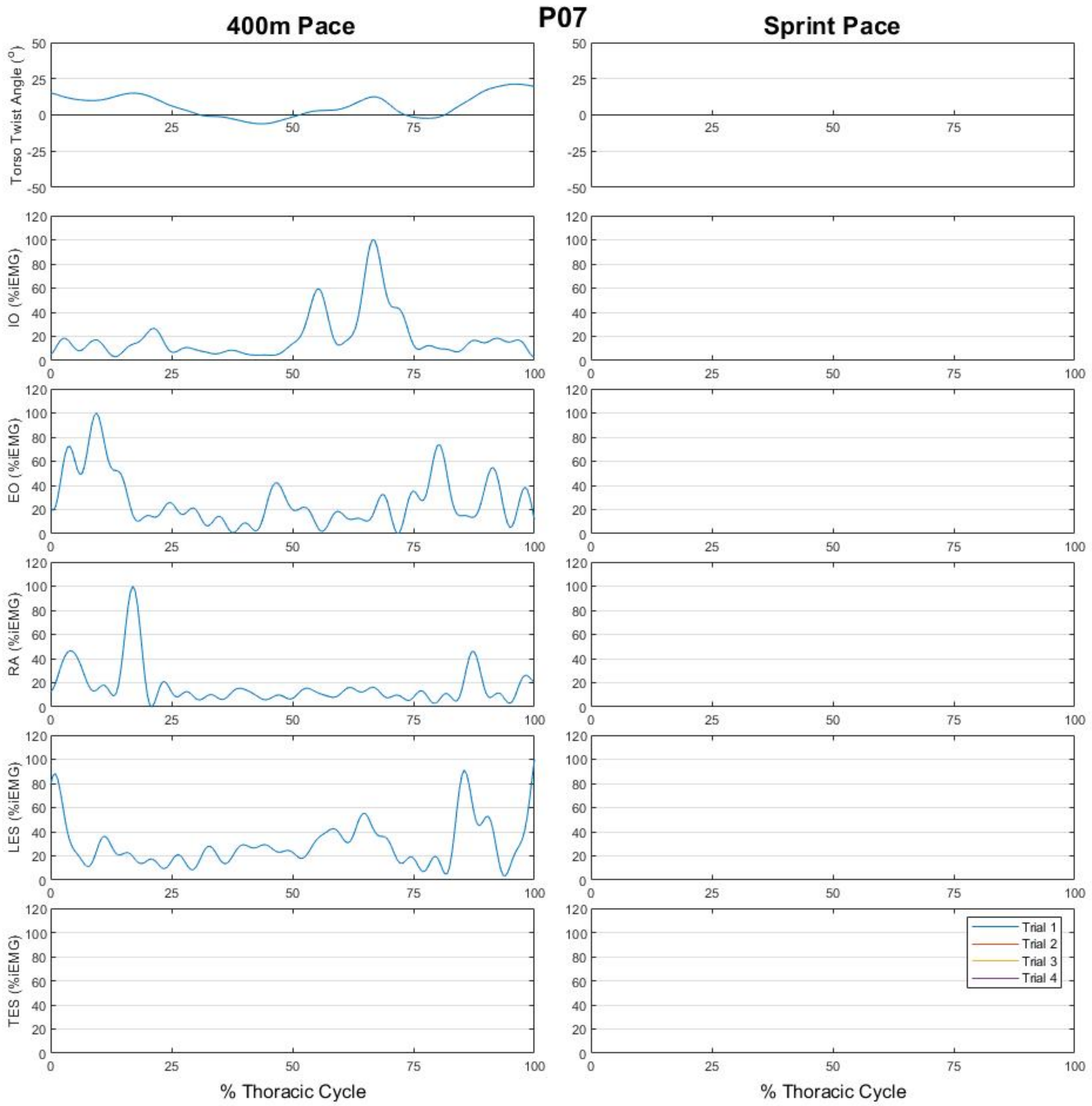

P02
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle

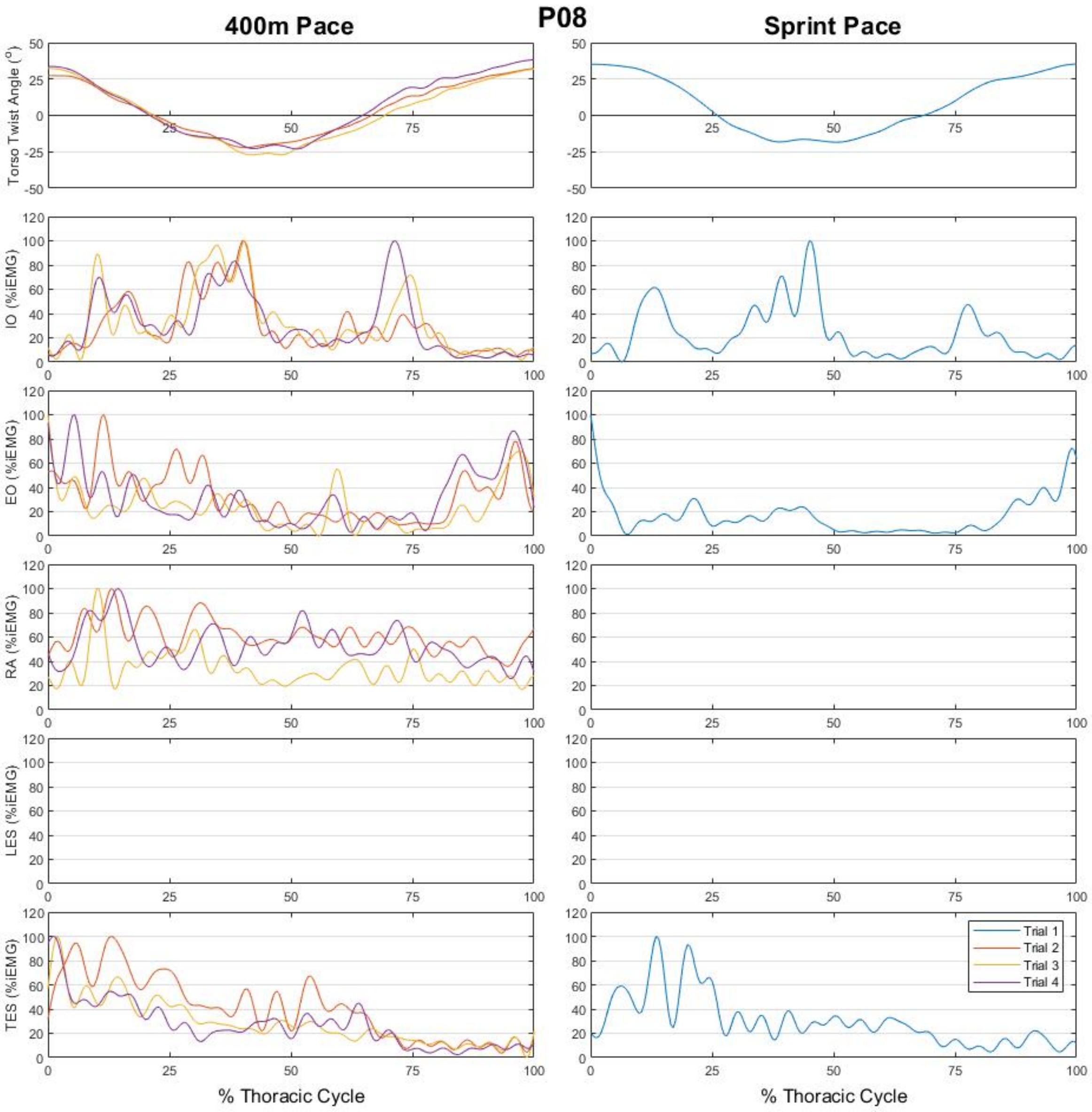

P03
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle

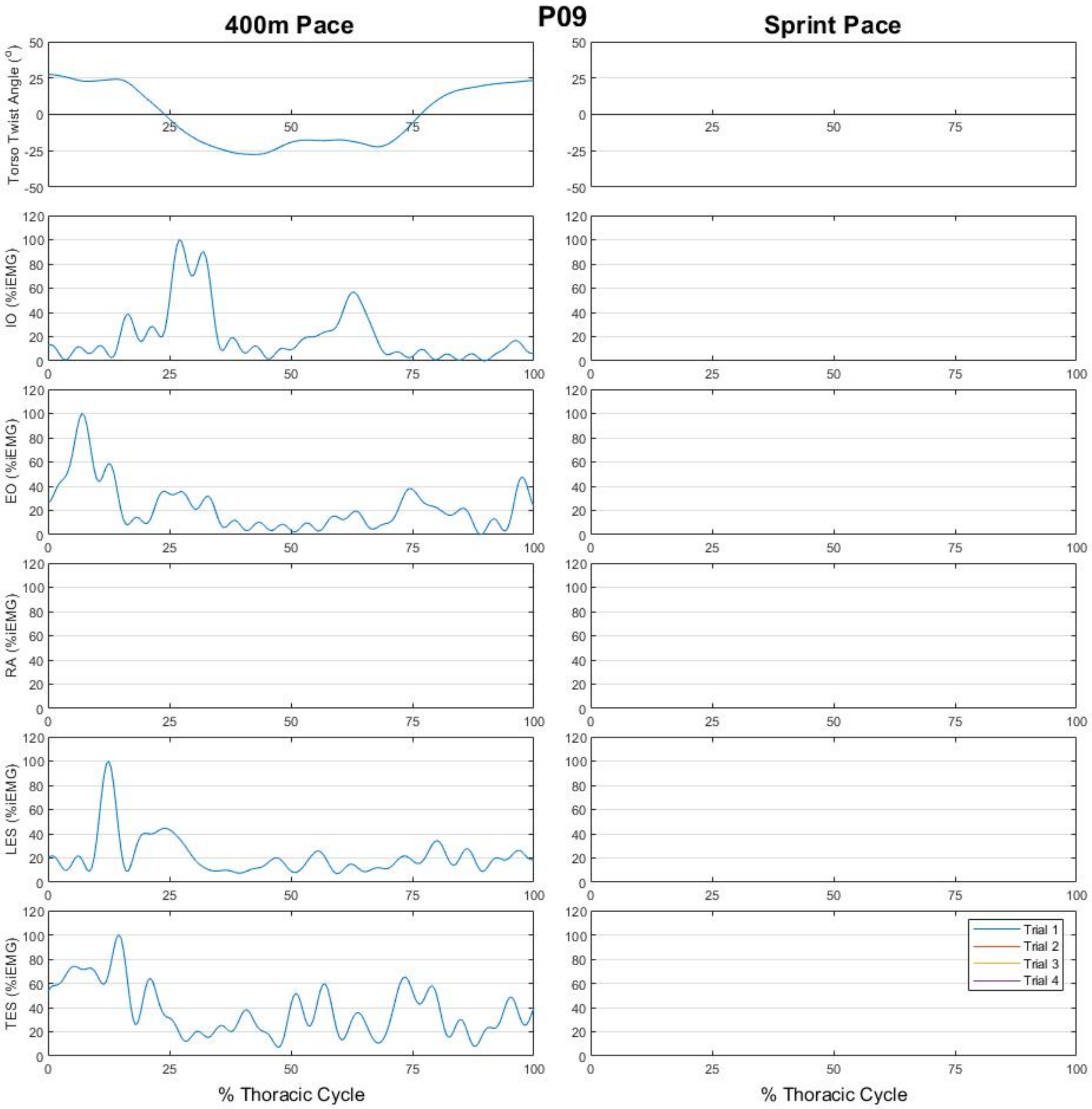

P04
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle

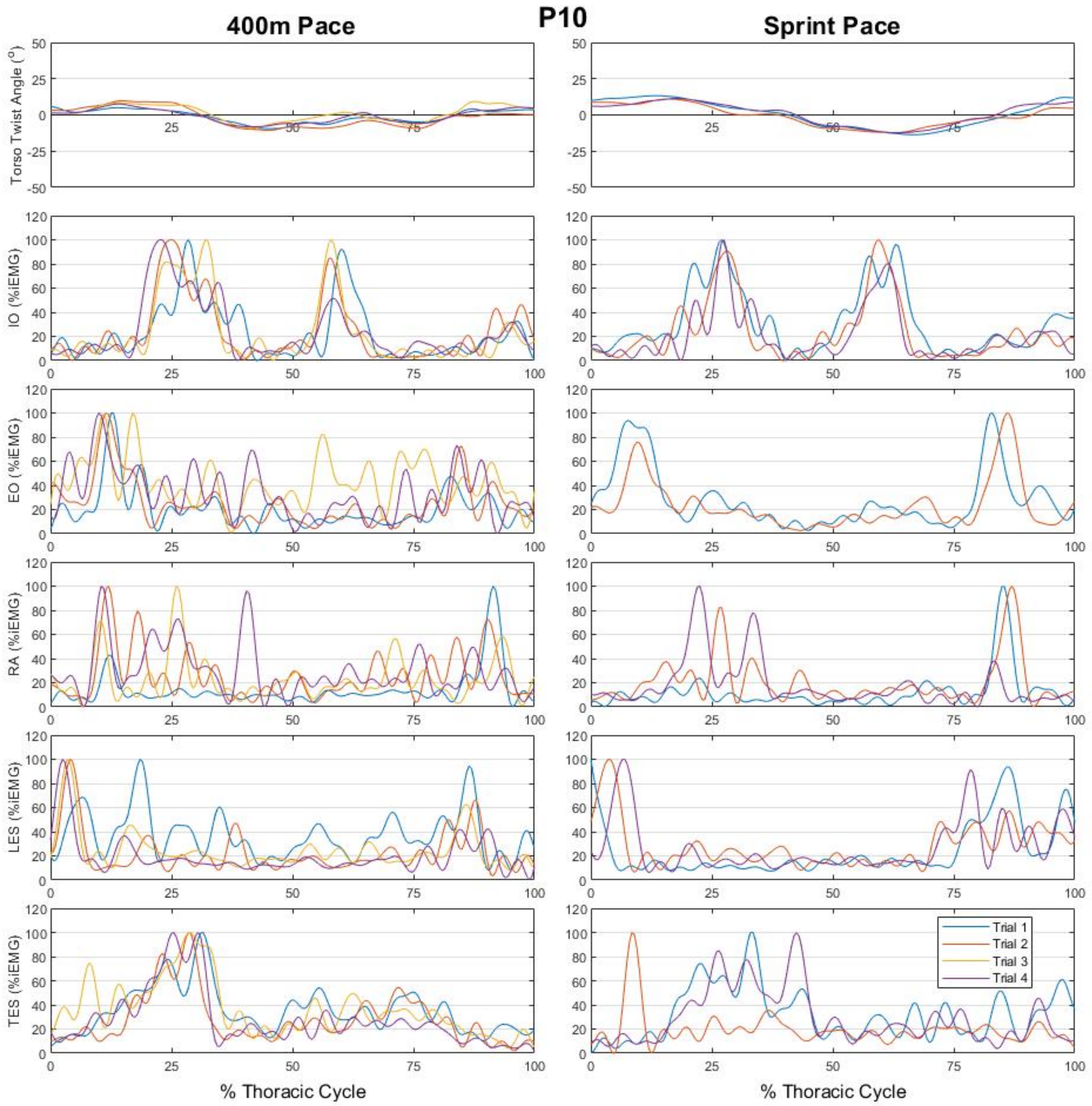

P05
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle

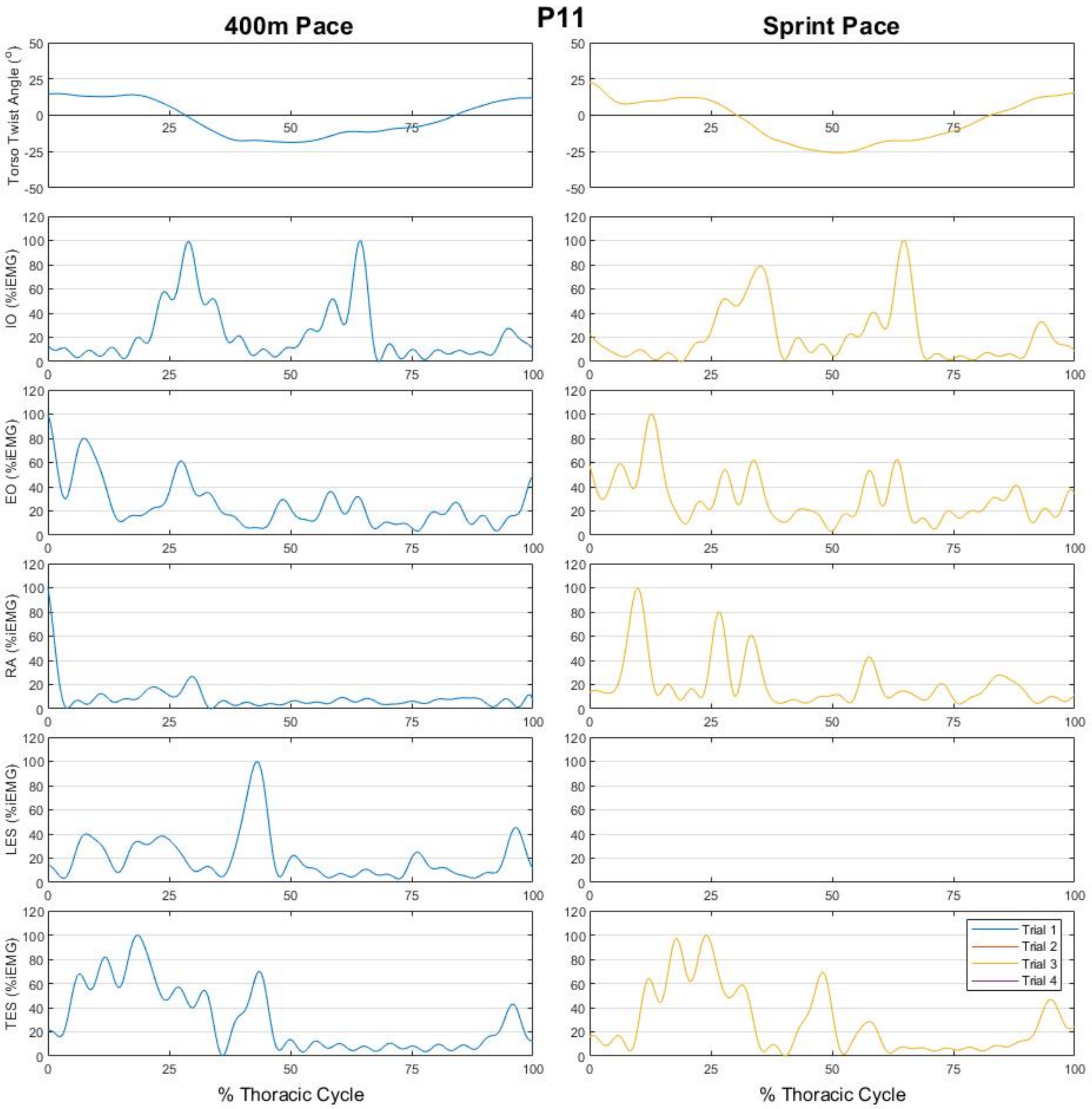

P06
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4

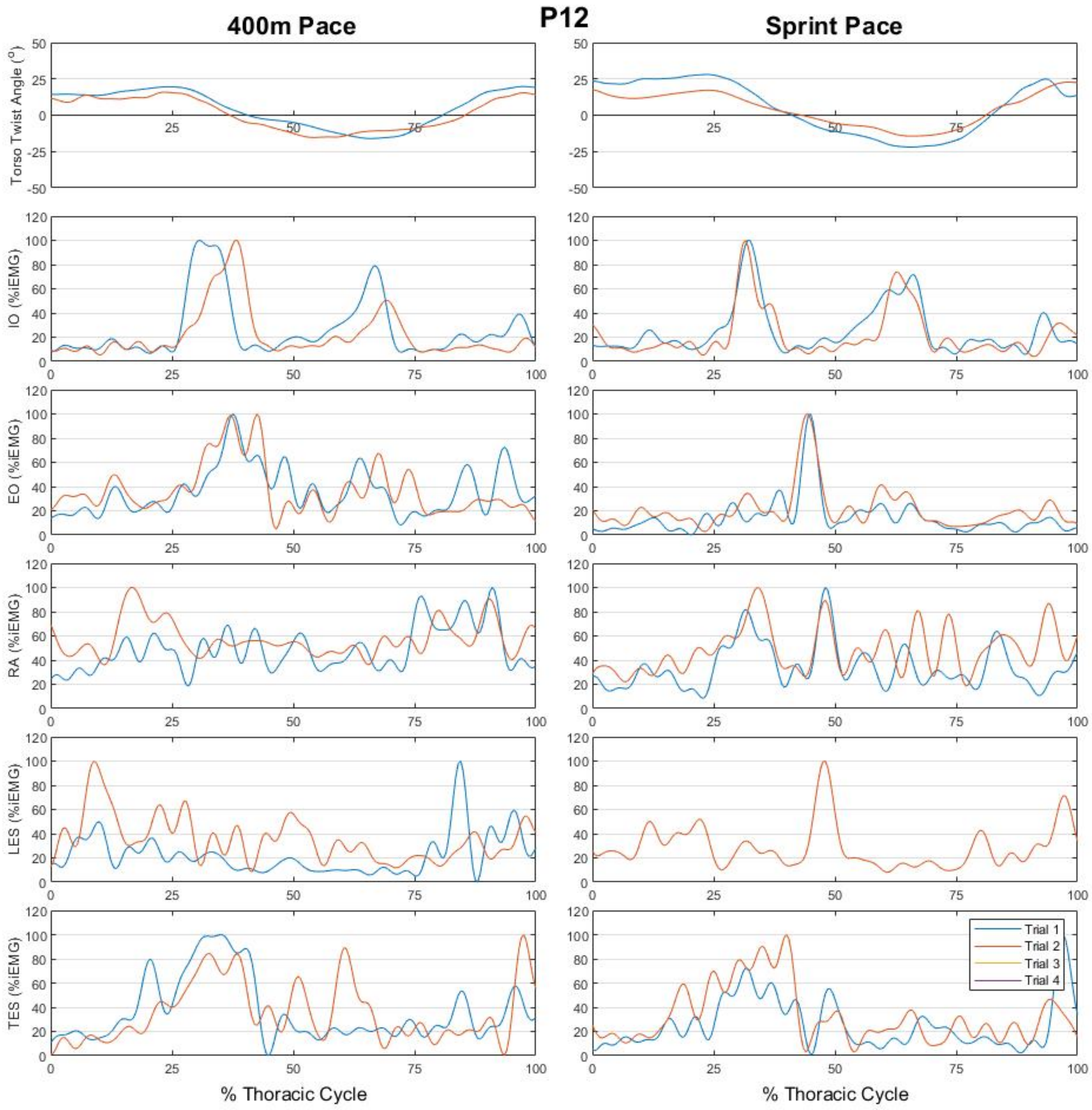

P07
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle

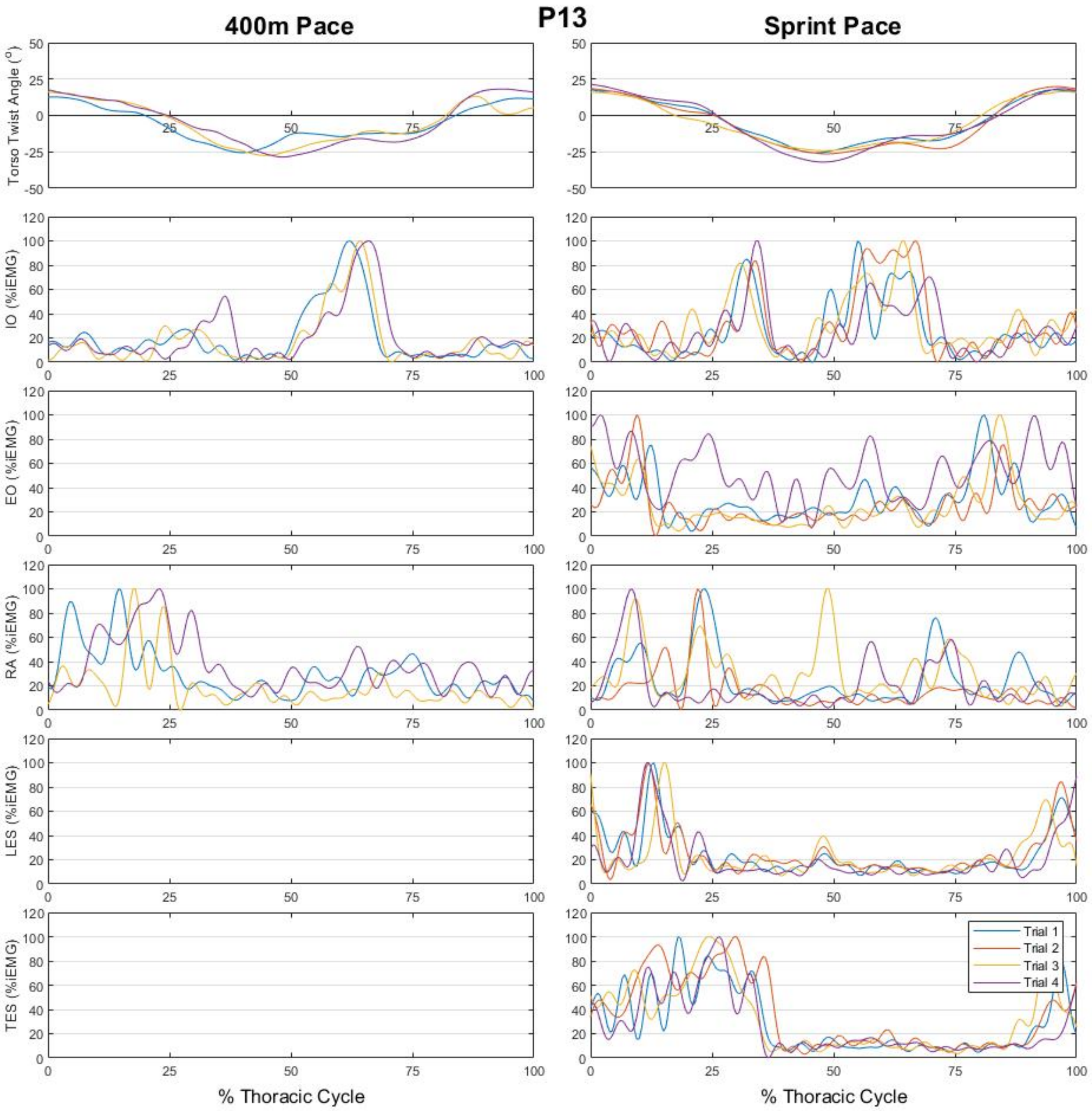

P08
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4

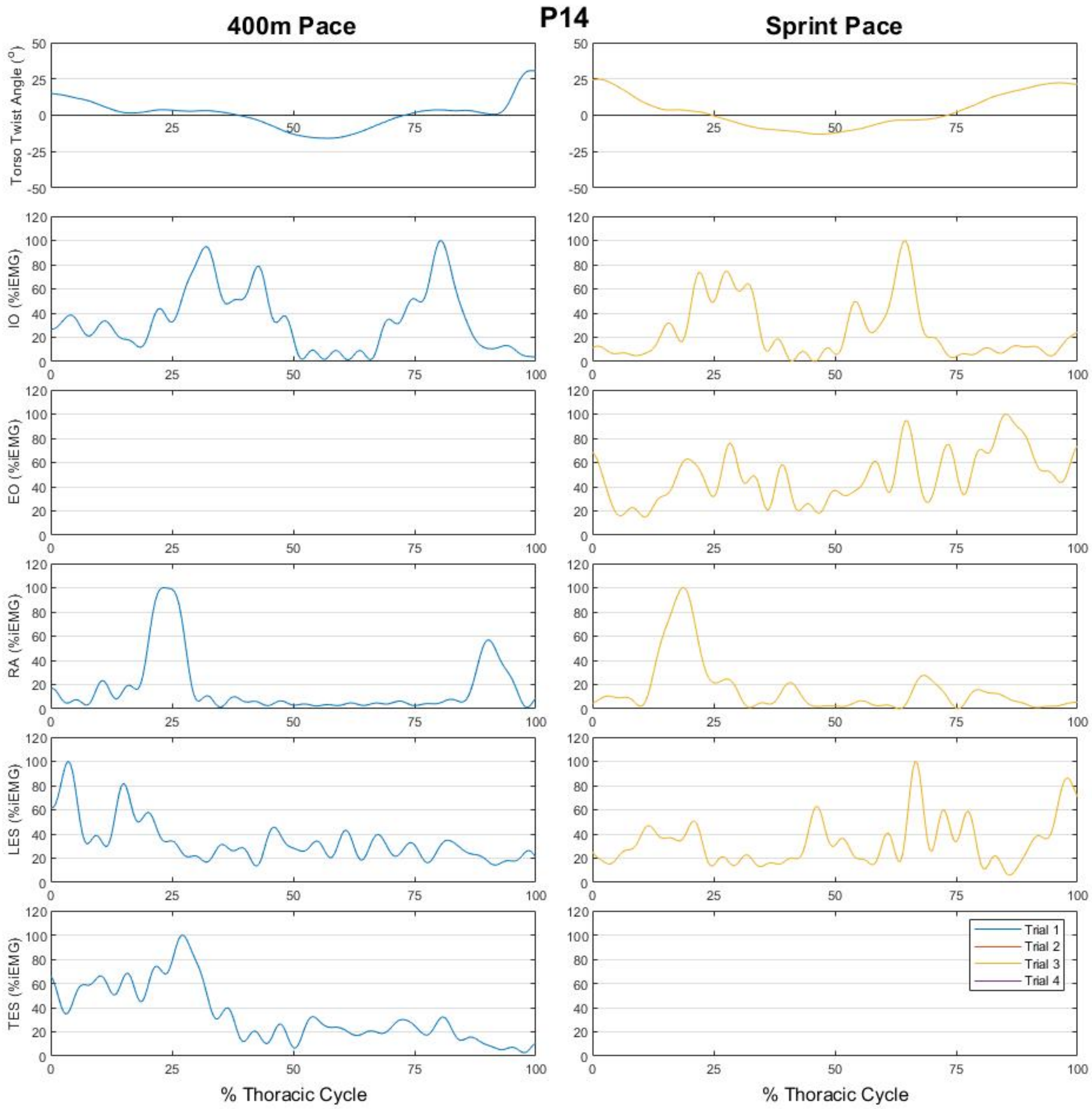

P09
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
0
25
50
75
100
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4

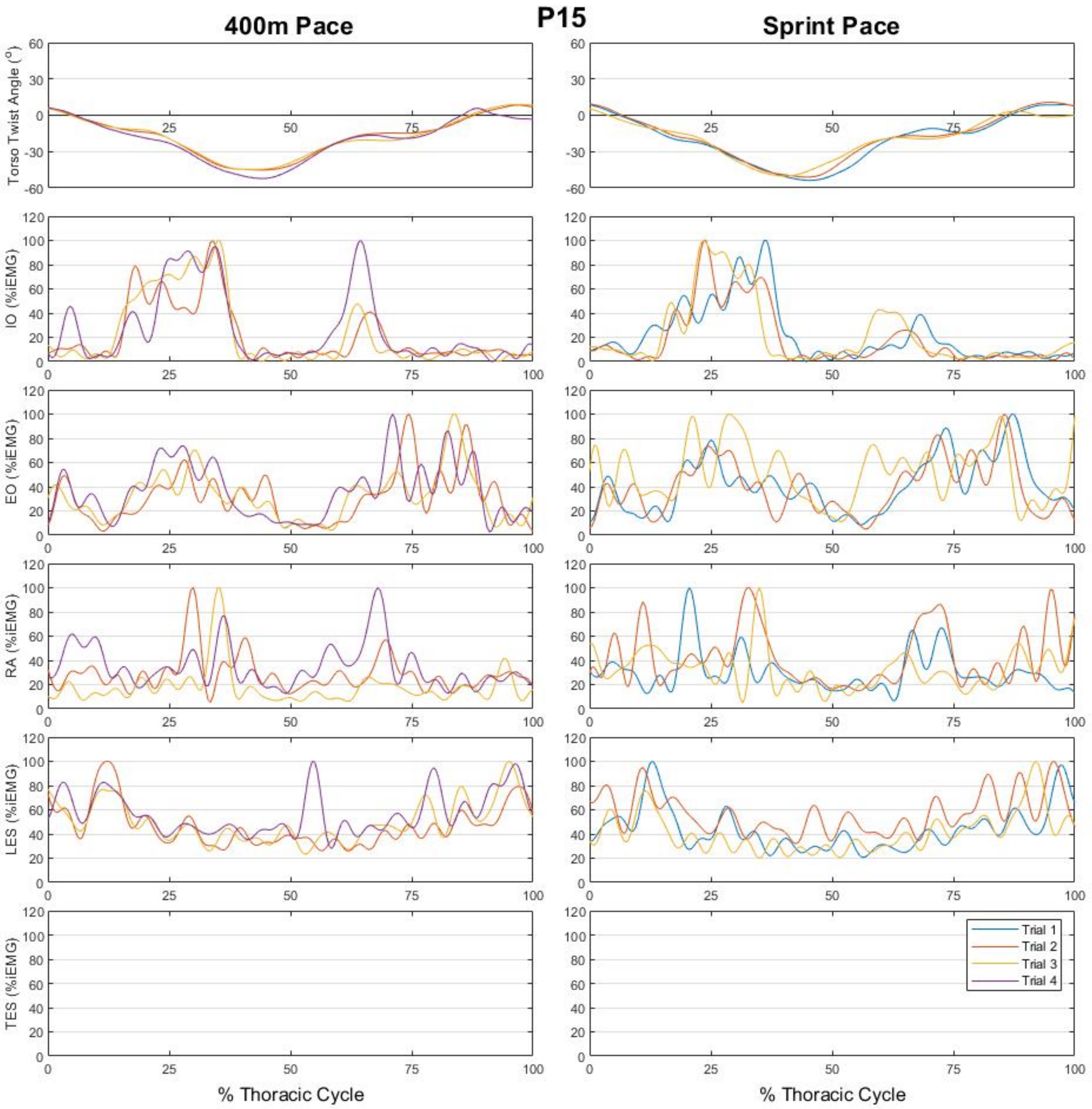

P10
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4


P11
400m Pace
Sprint Pace
Torso Twist Angle (°)
50
25
0
-25
-50
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
0
20
40
60
80
100
120
0
25
50
75
100
Trial 1
Trial 2
Trial 3
Trial 4
% Thoracic Cycle
% Thoracic Cycle


P12
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4


P13
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4


P14
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
50
25
0
-25
-50
120
100
80
60
40
20
0
25
50
75
100
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4


P15
400m Pace
Sprint Pace
Torso Twist Angle (°)
IO (%iEMG)
EO (%iEMG)
RA (%iEMG)
LES (%iEMG)
TES (%iEMG)
60
30
0
-30
-60
120
100
80
60
40
20
0
25
50
75
100
% Thoracic Cycle
% Thoracic Cycle
Trial 1
Trial 2
Trial 3
Trial 4

APPENDIX G:

Paper presented at the 36th International Conference on Biomechanics in Sports 2018

THE APPLICATION OF FOURIER ANALYSIS TO DEMONSTRATE THE IMPACT OF THE FLUTTER KICK ON LONGITUDINAL ROTATION IN FRONT CRAWL

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The contribution of the flutter kick to front crawl performance from its influence on longitudinal body rotation has not been thoroughly investigated. Fourier analysis was used to examine the impact of the kick on segmental and whole body angular momentum about the body's longitudinal axis in fourteen elite front crawl specialists swimming at sprint and 400m pace. The third harmonic frequency, representing the effects of the six-beat flutter kick, was greater at sprint than 400m pace in lower limb, upper limb, and whole body angular momentum. The presence of the third harmonic in upper limb and whole body angular momentum indicates that the flutter kick has an influence on longitudinal body rotation. The role of the flutter kick in front crawl performance may be linked to actions of the torso muscles to help control longitudinal body rotation.

KEYWORDS: Swimming, body roll, Fourier series, angular momentum.

INTRODUCTION: The flutter kick has the potential to improve the effectiveness of the front crawl stroke by influencing longitudinal rotation to enhance the propulsion from the arm stroke (Watkins & Gordon, 1983); however, empirical investigations of the impact of the flutter kick on longitudinal rotation in front crawl swimming are lacking. Analyses of segmental angular momentum have been used in other sports to explain the role of limb movements for performance; for example in running, the angular momentum of the upper limbs is out of phase with that of the lower body to balance the axial rotations of the lower limbs (Hinrichs, 1990). Due to the differences in frequencies between the two-beat rhythm of body roll and the six-beat rhythm of the flutter kick in front crawl, the timing of longitudinal rotation from the flutter kick is not perfectly in phase or out of phase with body roll. A different approach is therefore needed to analyse the effects of the flutter kick on longitudinal body rotation in front crawl. The repetitive nature of front crawl permits the use of Fourier analysis to represent longitudinal body rotation as a Fourier series of harmonic frequencies. The two-beat rhythm of body roll, for instance, can be represented by the first harmonic frequency while the six-beat rhythm of the flutter kick can be represented by the third harmonic frequency (Sanders & Psycharakis, 2009). In this way, Fourier analysis can be used to investigate the transmission of longitudinal rotation from the flutter kick to the rest of the body by examining the amplitude of the third harmonic in longitudinal angular momentum. Since flutter kick intensity is greater in faster swimming paces than at slower swimming paces (de Jesus et al., 2016), a comparison of the harmonic frequencies in the angular momentum signal at different swimming speeds would provide further information about the influence of the flutter kick on longitudinal body rotation. Fourier analysis was therefore used in this study to examine the frequency components of angular momentum data obtained from elite swimmers swimming at two different front crawl speeds to explore the impact of the flutter kick on longitudinal rotation.

METHODS: Digitised three-dimensional coordinate data of sixteen body segments of fourteen elite male Scottish front crawl specialists (age: 17.50 ± 1.91 years; height: 181.89 ± 5.47 cm; mass: 72.45 ± 6.86 kg) previously collected for studies of McCabe, Psycharakis, and Sanders (2011) and McCabe and Sanders (2012) were analysed. Participants were either sprint (50m) or middle distance (400m) swimmers who had specialised in front crawl for a minimum of two years, were not currently injured or recovering from injury, and held a short course personal best time of less than 24.60s for 50m or less than 4min10s for 400m. The data comprised one stroke cycle (SC), defined as the moment of hand entry into the water to the subsequent entry of the same hand, from four 25m sprint trials. From a 400m effort, one SC from the first 25m length of each 50m lap was selected for laps 2, 3, 4 and 5, totalling four observations at 400m pace. These were selected to align with previous findings that laps 1, 7 and 8 were consistently different for laps 2-6 (McCabe & Sanders, 2012). Lap 6 was excluded to further minimise the effect of fatigue on swimming technique.

Body segment parameters required for calculation of segment and whole body centres of mass and angular momentum were those obtained by McCabe (2008) using the "eZone" program (Deffeyes & Sanders, 2005) based on the elliptical zone method established by Jensen (1978). The body segment parameter data and manually digitised position data from each trial were then entered into a bespoke MATLAB (Mathworks, Inc.) analysis program written by the fourth author to calculate segmental and whole body centre of mass at each point in the SC. An additional 30 frames at each end of the SC were extrapolated by reflection to prevent data loss during filtering. Fourier transform with a 6 Hz cut-off was used to smooth the data. SC length was standardized to 201 points using Fourier transform and inverse transform so that each datum represented a half percentile of the SC (i.e. 0-100%).

Angular momentum of the lower limbs (LL – sum of local and transfer terms of the left and right foot, shank, and thigh), upper limbs (UL – sum of local and transfer terms of the left and right hand, forearm, and upper arm), and whole body (WB) were calculated about the longitudinal axis of the body's centre of mass for each ith percentile of the SC:

$$H_{si} = \sum HL_{si} + \sum HT_{si}$$

where HL_s is the local term, HT_s is the transfer term, and H_s is the angular momentum of each group of s segments.

HL_s and HT_s were calculated using the Newtonian equation (i.e. $H = I\omega$) as the product of moment of inertia and angular velocity of each segment about its own centre of mass (HL_s) and about the longitudinal axis of the body's centre of mass (HT_s), respectively.

A Fourier analysis was used to decompose the angular momentum signals into the first three harmonic frequencies (see Kreyszig (2006)). In front crawl swimming, the first harmonic (H1) is associated with the two-beat rhythm of body roll and the third harmonic (H3) is associated with the six-beat rhythm of the flutter kick (Sanders & Psycharakis, 2009). The amplitude (C) of each nth Fourier harmonic frequency was determined as:

$$Cn = (An^2 + Bn^2)^{0.5}$$

where, An and Bn are the sine and cosine coefficients.

The proportions of average power (i.e. the mean squared value) comprising the first and third harmonic, respectively, were determined as a percentage of angular momentum signals as:

$$2Cn^2$$

Separate paired t-tests were used to compare the amplitudes of H1 and H3, independently, in LL, UL, and WB between sprint and 400m pace ($\alpha = 0.05$).

RESULTS: Time series data of angular momentum and the corresponding H1 and H3 frequency components are shown in Figure 1 for a typical SC at sprint pace and 400m pace. Average power of H1 and H3 in each angular momentum variable is presented in Table 1. H3 dominated LL, comprising almost 90% of the signal at sprint pace and over 70% at 400m pace. Though H1 comprised the majority of UL (approximately 75%), H3 accounted for approximately 17% of UL at both paces. H3 was over 40% of WB at sprint pace and more than 25% at 400m pace. Figure 2 shows the amplitudes of H1 and H3 at sprint and 400m pace. H1 in LL was greater at 400m pace ($p < 0.05$), while H1 in UL was greater at sprint pace ($p < 0.01$). There was no difference in H1 amplitude in WB. H3 was greater at sprint pace for all angular momentum variables ($p < 0.05$).

DISCUSSION: This study demonstrated the use of Fourier analysis to illustrate the impact of the flutter kick on longitudinal body rotation. At both sprint and 400m pace, the flutter kick had a notable influence on upper limb and whole body angular momentum. The differences in H3 of LL between paces observed in this study (Figure 2) aligns with findings that the six-beat flutter kick is associated with faster swimming (Chollet, Chalies, & Chatard, 2000). It could be expected that the size of the difference in H3 of UL between paces would be similar to the difference in H3 of LL; however, there was a much smaller disparity between the paces of H3 in UL than LL, indicating that the torso muscles have a role in controlling longitudinal rotation from the flutter kick. A "filtering" of the six-beat rhythm by the torso muscles may diminish the amount of rotation transferred from the lower limbs to the upper limbs. Furthermore, this "filtering" effect seems to be more prevalent at sprint pace, suggesting a greater demand on the torso muscles in faster swimming. Identification of torso muscle activation profiles in front crawl is required to test this hypothesis.

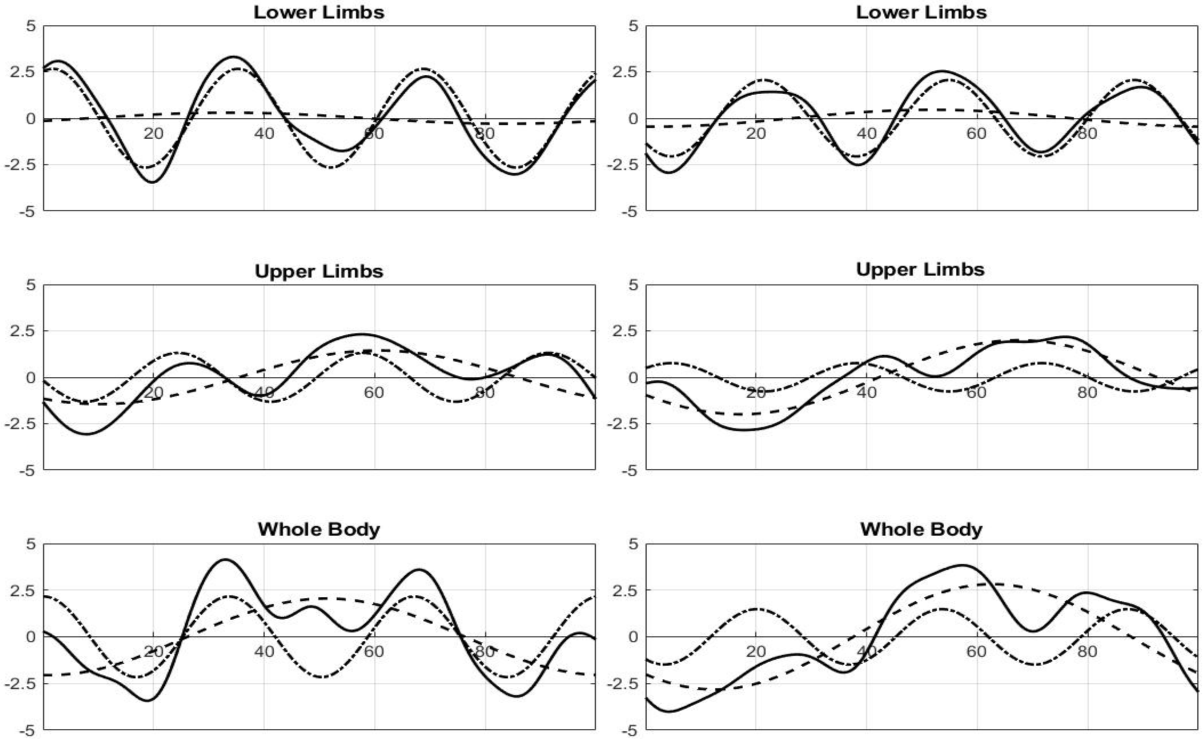

Figure 1. Time series of angular momentum (kg·m^2/s) for one stroke cycle at sprint (left) and 400m pace (right). Solid lines show angular momentum, dashed lines are the first harmonic frequency (H1), and dash-and-dot lines are the third harmonic frequency (H3) for each signal.

Table 1. Mean (*SD*) of amplitude (%power) of the first (H1) and third (H3) harmonic frequency in lower limb (LL), upper limb (UL), and whole body (WB) angular momentum.

		H1		H3	
		Sprint	400m	Sprint	400m
LL	Mean	2.9%	14.6%	89.1%	71.1%
	SD	*2.4%*	*13.0%*	*5.7%*	*17.9%*
UL	Mean	75.6%	74.6%	17.1%	16.9%
	SD	*9.2%*	*7.6%*	*8.7%*	*6.6%*
WB	Mean	48.7%	64.9%	41.5%	27.1%
	SD	*12.2%*	*13.2%*	*14.8%*	*13.7%*

Though the upper body does not rotate about the longitudinal axis with a six-beat rhythm in experienced swimmers, there was a clear impact of the flutter kick on UL in this study. The presence of the third harmonic in UL could have been a byproduct of the "stabilising" role of the flutter kick (see Watkins and Gordon (1983)). The rotation produced by the flutter kick, though its purpose may have been to control torso rotation, was also transferred to the upper limbs. Similar to the benefits of the arm swing in running, the flutter kick could produce a countering effect to control longitudinal torso rotation in front crawl. In this way, the flutter kick could improve the effectiveness of the stroke by helping swimmers direct propulsion from the arms towards the intended swimming direction. In contrast, swimmers may also use the movements of the lower limbs to facilitate longitudinal rotation. Yanai (2003) proposed that fluid forces from the flutter kick contribute to longitudinal rotation, allowing swimmers to generate more forward propulsion from the arm stroke rather than “wasting” fluid forces from the arms to drive body roll. Further investigation is needed into the timing and sequencing of lower limb movements and longitudinal body rotation to improve understanding of the different roles of the flutter kick in front crawl performance.

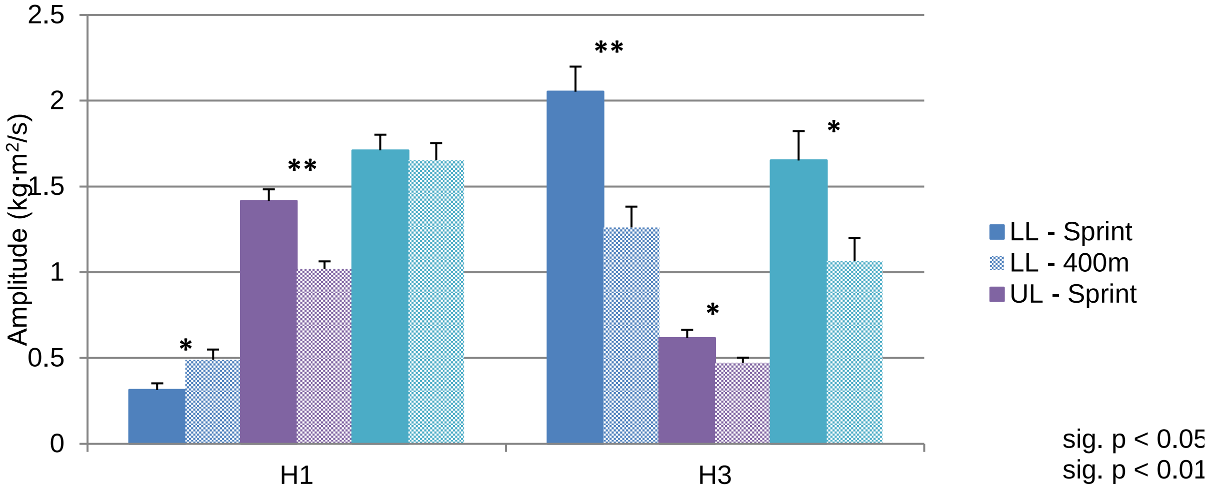

Figure 2. Mean H1 and H3 amplitude in angular momentum at sprint and 400m pace. Error bars represent standard error.

CONCLUSION: Fourier analysis is a powerful tool that can be used to determine the impact of segmental motion on body rotation. The findings suggest an important role of the torso muscles in controlling longitudinal rotation from the flutter kick in front crawl. Furthermore, the impact of the flutter kick on longitudinal body rotation presented here indicates that lower limb movements could be help control body roll. The findings from this study provide a foundation for discussions with coaches and athletes to maximise performance.

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APPENDIX H:

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DO THE TORSO MUSCLES PRODUCE TORSO TWIST IN FRONT CRAWL?

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The purpose of this study was to investigate the association between torso muscle activity and torso twist. EMG data from five torso muscles and 3D motion capture data were recorded during 4x25m front crawl swimming trials at 400m and 50m pace (N=15). EMG data were integrated over 10ms intervals and normalized to the maximum value during each swimming trial (%iEMG) and torso twist acceleration was calculated as the second time derivative of the relative angle between thorax and pelvis about the longitudinal axis. Spearman correlations were calculated between 5th percentile scores of %iEMG and torso twist acceleration. Mean correlation coefficients were weak (i.e. $r < 0.30$) for all muscles at both paces. The findings suggest that torso muscle activity may not be directly associated with torso twist acceleration.

KEYWORDS: swimming, electromyography, three-dimensional motion capture, kinematics.

INTRODUCTION: The body's rotation about the longitudinal axis in front crawl improves propulsion generation from the arms (Kudo, Sakurai, Miwa, & Matsuda, 2017) and reduces the risk of shoulder injury (Yanai & Hay, 2000). Swimmers are likely to benefit from improving their ability to control rotation between the upper and lower trunk. This may be why dry-land training exercises for swimmers tend to involve twisting movements of the trunk. However, it is unclear whether swimmers use their torso muscles to generate torso twist in front crawl, giving reason to question the specificity of exercises that involve active trunk twisting from the torso muscles. The acceleration of the thorax with respect to the pelvis depends on resolution of the equation of angular motion $\alpha = \Sigma T/I$ where T is torque acting on the thorax and I is the moment of inertia of the upper body including the thorax, head, and upper limbs. The torques acting on the thorax comprise the torque produced by the forces due to the actions of the arms, the buoyancy and gravitational forces, and the actions of the torso muscles. The angular motion of the pelvis depends on the torques due to the actions of the lower limbs, the buoyancy and gravitational forces, and the reactions to the actions of the torso muscles. Although the contributions of the forces to torque are not readily obtainable in swimming, knowledge of the relationship between torso muscle activity and rotational acceleration of the thorax with respect to the pelvis, or 'torso twist acceleration', may provide insights into the roles of the torso muscles in producing torso twist or in stabilizing the torso. Therefore, the purpose of this study was to investigate the association between torso muscle activity and torso twist.

METHODS: Fifteen male competitive swimmers (age: 20.4 ± 4.8 years; height: 177.6 ± 8.8 cm; mass: 69.6 ± 11.0 kg) were recruited for this study. Data collection was conducted in an indoor 25m pool. Participants completed a standardized 1000m warm up before being fitted with EMG apparatus and motion capture markers.

Ag-AgCl surface electrodes were adhered to the skin over internal oblique, external oblique, rectus abdominis, lumbar erector spinae, and thoracic erector spinae on the right side (Cram, Kasman, & Holtz, 1998). A reference electrode was placed on the right posterior superior iliac spine. Electrodes and EMG leads were covered with waterproof adhesive (Opsite Flexfix, Smith & Nephew Inc.). EMG data were sampled (BIOPAC Systems, Inc.) at 2000 Hz with a 16-bit A-to-D conversion and amplified (gain = 1100) with a common mode rejection ratio of 110 dB. Preamplifiers were enclosed in epoxy resin for waterproofing. Participants wore a full-body Speedo FASTSKIN™ swimsuit to help secure the EMG apparatus.

Participants' motions were captured at 100 Hz with Qualisys (Göteborg, Sweden) using 11 above water and six underwater cameras. The calibration volume (1.7 m width, 6.4 m length, 1.4 m height) was located 10m from the start wall. Reflective markers were placed over the left and right acromion and lateral aspect of the 10th rib at the mid-axillary line and a T-shaped rigid body (80mm x 100mm) with three reflective markers was placed over the sternum to track the thorax motion. Reflective markers were adhered over the left and right superior iliac crest, anterior superior iliac spine, and greater trochanter to define and track the pelvis motion.

Participants entered the pool and swam to the calibrated volume to stand on a platform and a calibration trial of the participant standing in the anatomical position was captured before participants returned to the start wall. The testing protocol comprised 4x25m front crawl at a pace equivalent to the participant's 400m race pace. Swimmers rested in the water for 5min before completing 4x25m trials at sprint pace. Each trial began from a push start and participants were required to not breathe as they entered the calibration volume (marked on the bottom of the pool) to avoid effects of breathing on swimming technique (Psycharakis & McCabe, 2011).

Three-dimensional marker data were filtered using a 4th order low pass Butterworth filter with a 6 Hz cut-off. Thorax and pelvis angular displacements about the global horizontal axis in the swimming direction were calculated. Torso twist angle was the difference between thorax and pelvis angular displacements. Positive and negative values represent counter-clockwise and clockwise rotation, respectively, when viewing the swimmer head-on. Torso twist acceleration was the second time derivative of torso twist angle. One cycle of thorax rotation, defined from peak counter-clockwise thorax rotation to the subsequent peak counter-clockwise thorax rotation, was selected from each trial. Swimming velocity was calculated by dividing thorax horizontal displacement by the time to complete one thorax rotation cycle (m/s). Due to marker occlusion during data collection, the thorax and pelvis could not be reconstructed for the duration of one complete thoracic cycle for some trials. These trials were omitted from analysis. Across all participants, 33 trials at 400m pace and 21 trials at sprint pace contained thorax and pelvis data for every frame of one complete thorax rotation cycle and were used for analysis.

Raw EMG data were band pass filtered (4th order Butterworth, 20 to 500 Hz). The mean was subtracted from the filtered EMG and a full-wave rectifier was applied. Full-wave rectified EMG was integrated over 10ms intervals of the thoracic cycle to match the sampling frequency of the motion capture data (i.e. 100 Hz). Integrated EMG and torso twist acceleration were standardized to 201 points of the thoracic cycle using Fourier transform and inverse transform (Sanders, Gonjo, & McCabe, 2015) such that each datum represented a half percentile (i.e. 0-100%). Integrated EMG data were then divided by the maximum value from each trial to produce a percentage of maximum muscle activity (%iEMG) for each percentile of the thorax rotation cycle. Ensemble averages and 95% confidence intervals (95%CI) of the true mean were calculated for torso twist acceleration and %iEMG for each percentile of the thorax rotation cycle at both paces. Confidence intervals were calculated as the z-score (determined using the t-distribution of the sample size) multiplied by the standard error of the sample mean. Percent iEMG and torso twist acceleration were averaged for every 5th percentile of the thorax rotation cycle, producing twenty scores for %iEMG and torso twist acceleration over the entire cycle for each trial. %iEMG data were not normally distributed. Therefore, Spearman Rank-Order correlation tests were used to correlate 5th percentile %iEMG scores with 5th percentile torso twist acceleration scores over the entire thorax rotation cycle. Five separate tests (one for each muscle) were conducted for each trial at both paces to explore the relationships between %iEMG and torso twist acceleration. The mean and range of the correlation coefficients across participants were analysed and interpreted using Cohen's (1988) recommendations (weak: $r < 0.30$; moderate: $r = 0.30$ to 0.50 strong: $r > 0.50$).

RESULTS: Average swimming velocity was 1.4 ± 0.1 m/s and 1.6 ± 0.1 m/s at 400m and sprint pace, respectively. There were two peaks in internal oblique activity at both paces: one between 20 to 40% and one between 50 to 70% of the thoracic cycle (Figure 1). During these parts of the cycle, torso twist acceleration acted in both the clockwise and counter-clockwise directions with no obvious pattern with respect to the changes in internal oblique activity. Similarly, the increases in external oblique activity at the beginning of the cycle at both paces and at 80% of the cycle at sprint pace did not seem to relate to changes in torso twist acceleration. There were no clear patterns between torso twist acceleration and the changes of rectus abdominis, lumbar erector spinae, or thoracic erector spinae activity at either pace. Mean correlation coefficients for the relationships between %iEMG and torso twist acceleration were weak for all muscles at both paces. The range of coefficient values from individual participants was large for every correlation (Table 1).

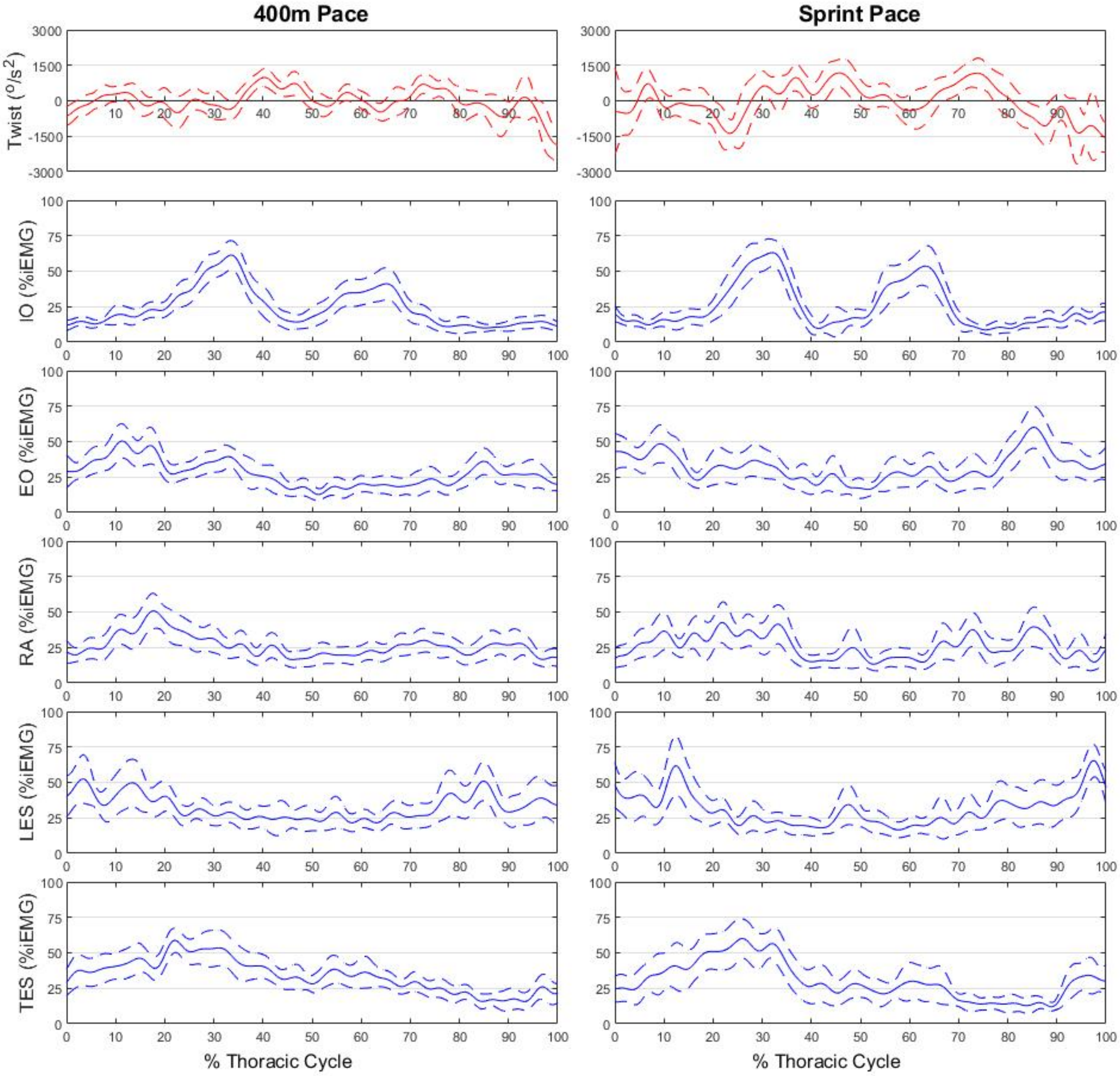

Figure 1. Time series graphs of ensemble averages (solid lines) with 95%CI of the true mean (dashed lines) for torso twist acceleration (top) and %iEMG (bottom five) at 400m (left) and sprint pace (right).
IO = internal oblique, EO = external oblique, RA = rectus abdominis, LES = lumbar erector spinae, TES = thoracic erector spinae.

Table 1. Mean (range) of Spearman correlation coefficients (*r*) between torso muscle %iEMG and torso twist acceleration at 400m pace and sprint pace.

	Internal Oblique	External Oblique	Rectus Abdominis	Lumbar Erector Spinae	Thoracic Erector Spinae
400m Pace	-0.09 (-0.54 to 0.34)	-0.05 (-0.34 to 0.26)	-0.05 (-0.53 to 0.56)	-0.13 (-0.63 to 0.30)	-0.03 (-0.39 to 0.35)
Sprint Pace	-0.07 (-0.34 to 0.37)	-0.18 (-0.61 to 0.29)	-0.03 (-0.32 to 0.39)	-0.11 (-0.40 to 0.31)	-0.15 (-0.51 to 0.17)

DISCUSSION: This is the first study in the existent literature about the relationship between torso muscle activity and torso twist in front crawl swimming. The findings presented here help develop our understanding of the roles the torso muscles may (or may not) play in front crawl performance and have implications for training.

Torso twist acceleration did not display a direct relationship to muscle activity at either pace, suggesting that the torques that produce torso twist are mainly from sources other than the torso muscles, for example, possibly from the actions of the arms and legs. Rather than generating rotation between the upper and lower torso, swimmers may use the torso muscles to stabilize the spine. This could help control the effects of external torques generated by the arm stroke and flutter kick so that rotation about the longitudinal axis is optimal for performance. Further, the torso muscles provide spine stability for generating forces that produce limb movements (Hodges, Cresswell, Daggfeldt, & Thorstensson, 2000; Hodges & Richardson, 1997). The spine stability provided by the torso muscles may enhance the effectiveness of the arm stroke and flutter kick by creating a platform from which hydrodynamic reaction forces can be generated for forward propulsion.

Considering the importance of the torso muscles for spine stability during axial trunk rotation (Marras & Granata, 1995), there is also a possibility that swimmers use the torso muscles to help maintain trunk posture in front crawl as one of their main roles. Rotation about the longitudinal axis is also influenced by the side to which a swimmer prefers to breathe, even when they do not take a breath during a stroke cycle (Psycharakis & McCabe, 2011). The association between torso muscle activity, posture, and preferred breathing side should be investigated to further improve our understanding of the torso muscle roles in front crawl.

CONCLUSION: Torso muscle activity is not directly associated with torso twist acceleration in 400m and 50m front crawl swimming. The torso muscles may be more important for optimizing longitudinal body rotation, producing spine stability to assist the limbs in generating motion, and maintaining trunk posture. Further research is required to investigate these potential roles of the torso muscles. Exercises that require swimmers to generate axial spine rotation with the torso muscles may not necessarily improve the specificity of dry-land training for front crawl. Training may be better directed towards strengthening the torso muscles to improve their function in maintaining posture and stability to optimize performance.

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