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DEPARTMENT OF SPORT AND EXERCISE SCIENCES

PHYSICAL DEVELOPMENT OF SAILORS WITHIN THE BRITISH SAILING TEAM'S OLYMPIC PATHWAY

By

Timothy John Jones

Thesis for the Doctor of Philosophy

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ABSTRACT

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Elite sailing is a complex sport that requires the combination of many factors (Sjøgaard *et al.*, 2015). In particular physical characteristics have become more important, as recent format changes in elite sailing have resulted in a more competitive and physically demanding environment (Bojsen-Möller *et al.*, 2014). Considering the increased competitiveness of elite senior sport (DeBosscher *et al.*, 2007) maintaining a constant stream of athletes capable of elite success must be achieved for success (Vaeyens *et al.*, 2009). This thesis aimed to improve the understanding of physical development below Olympic level to optimise the British Sailing Team's Olympic pathway programme.

The first experimental chapter identified components of fitness and anthropometrical characteristics of successful elite development in sailing using semi-structured interviews with a sample of experienced elite coaches and top world ranked sailors, including multiple Olympians. Commonality was observed across the majority of physical characteristics, revealing a high level of agreement, increases in physical demands at transition points emerged as a key aspect. The second experimental chapter investigated the reliability, validity and inter-relationships of upper body strength assessments for inclusion in the Olympic pathway physical testing battery. Press-up and Supine pull tests were shown to be reliable (ICC = 0.98) and valid when correlated to 1RMs (r = 0.92 to 0.98). This combined with the time-conscious environment of mass field testing within the Olympic pathway, resulted in these tests chosen as upper body strength testing methods within the physical testing battery. The third experimental chapter explored methods used to predict Peak Adult Height (PAH), establishing the approach of Khamis and Roche (1995) to best predict PAH and estimate maturation status in Olympic pathway sailors. Confidence in these methods enables greater individuality in the monitoring of sailor progression. Using the physical profiling testing battery, the next chapter identified the physical characteristics of elite Junior and Youth sailors, filling the gap of understanding below Olympic level. The final experimental chapter identified the intra- and inter-individual variation of physical development in pathway sailors relative to biological age-derived benchmarks.

This thesis provides a detailed understanding of the physical development of elite sailors within the British Sailing Team's Olympic pathway, confirming key characteristics of successful elite development and a sailing-specific physical testing battery to enable assessment of a broad set of physical competencies required to meet the changeable Olympic class environment. Application of this physical testing battery has generated a novel cross-sectional analysis of pathway sailing classes in males and females, providing the first insight into physical requirements of sailors below Olympic level. The individual variation in physical development though the Olympic pathway has been highlighted, reflecting the need for longitudinal monitoring of sailors relative to biological age.

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Declaration of Ownership

I, Timothy John Jones

declare that the thesis entitled

Physical development of sailors within the British Sailing Team's Olympic pathway

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

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- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
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There are so many people that have been involved in completing this thesis that I am sure I will have missed someone – so apologies in advance! Where do I start? Maybe at the beginning – my parents have been there since day one and have supported me through many challenges and I owe them more than words can describe, and they may be the most surprised that their youngest son ended up becoming a PhD student from a slightly troubled early track record with education. Sorry I haven't really seen you over the last couple of years.

My wife Emily deserves a medal for her patience and support, specifically over the last year, but also for sticking with me moving home every couple of years to follow my working progression. I am looking forward to getting some weekends and evenings back to spend some more time with you.

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Paralympic athletes for the 2016 Rio Olympic Games. I feel so lucky to have spent a rich five years in one of GB's most successful Olympic sports and currently the top sailing nation in the world. I will miss all the staff down in Weymouth and in Hamble, where I made some good working relationships and great friends. To all my profiling testers, who spent hours in vans, trapped, listening to me rambling on, sweeping and mopping sports hall floors in the late hours and early starts maintaining order and consistency in sometimes challenging environments – I hope you all have learned a lot from your time working as part of the team, and enjoyed it.

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Thanks to you all.

Definitions and Abbreviations

%PAH – Percentage of Peak Adult Height
20 m SRT - multistage 20-metre shuttle run test
APHV – Age at Peak Height Velocity
BA – Biological Age
CA – Chronological Age
CI – Confidence Interval
CYD – Composite Youth Development
DMSP – Developmental Model of Sports Participation
DYNO – Concept II Dynamometer
HRmax – Maximum heart rate
ICC – Intra Class Correlation
ISAK – The International Society for the Advancement of Kinanthropometry
LTAD – Long Term Athlete Development
MEVC% - Percentage of maximal evoked voluntary contraction
MOD – Mistral One-Design windsurf board
MPF - Mean Power Frequency
PAH – Peak Adult Height
PHV – Peak Height Velocity
r – Pearson's Product-moment correlation
RMS - Root Mean Square
RYA – Royal Yachting Association
S.D. – Standard Deviation
S&C – Strength and Conditioning
sEMG – Surface electromyography
SLJ – Standing Long Jump
TDE – Talent Development
TEM – Technical Error of Measurement
TID – Talent Identification
VMPU – Vermont Pull-up
$\dot{V}O_2max$ – Maximal oxygen uptake
$\dot{V}O_2peak$ – Peak oxygen uptake
YPD – Youth Physical Development

Chapter 1 General Introduction

1.1 Stimulation for the thesis

Creating a successful pathway that is able to systematically identify and develop a constant stream of athletes capable of producing elite medals will increase the probability of future success (Abernathy, 2008; Vaeyens *et al.,* 2009). Once identified as having potential for future success, resources may be focused to enhance the possibility of progression, such as provision of coaching, sports science support or funding (Vaeyens *et al.,* 2009). There is currently no research that investigates the developmental process of Olympic sailors. Elite sailing is a complex sport that requires the combination of many factors including decision-making, cognitive function, tactics and physical skills (Bojsen-Möller *et al.*, 2007; Sjøgaard *et al.,* 2014). Further complication is added by the unpredictable and ever changing environmental conditions on the water that are out of the sailor's control. For this reason the British Sailing Team have previously focused on a mission of "controlling the controllables" (Brown, 2010, p.5). One controllable area that has become particularly relevant is sailor physical preparation, as in recent Olympic cycles there have been advances in race format and boat design that have made elite sailing a more competitive and physically demanding sport (Bojsen-Möller *et al.*, 2014).

Therefore it is the aim of this thesis to further the current understanding of the physical development of elite sailors through building an objective evidence-based manuscript to help inform the Olympic pathway. This will include a review of current perspectives in talent research, the physical requirements of elite sailing, and confirming and profiling key characteristics of successful elite sailing development, investigating the progression of these characteristics within sailors on the Olympic pathway since 2012.

1.2 History of Sailing

Sailing as a method of transportation and recreation has existed for thousands of years, dating back as early as 2,600 BC in Egyptian times. It existed primarily as a means for travel over long distances or for transporting heavy loads using the wind as a power source where it would have been impossible to use human muscular power alone (Knox-Johnston, 1990).

The earliest reference to competitive sailing racing also referred to as sport sailing or yacht racing appears during the 1600's in the Netherlands. This structured activity was brought to British shores c.1660 by King Charles II (Knox-Johnston, 1990). Many different forms of sailing racing exist, ranging from the high budget big boat team events such as the long-distance Volvo Ocean Race and America's cup, to single and double-handed dinghy and boardsailing classes sailed in Olympic sailing. This thesis will focus on the context of Olympic sailing, in particular the developmental process or 'pathway' to Olympic competition.

1.3 Technical bases of sailing

Sailing uses the wind for forward propulsion. The way this is achieved is different relating to the direction of movement relative to the wind, in its most simple terms comprising of upwind (against the wind) and downwind (with the wind).

1.3.1 Sailing upwind

It is not possible to sail directly into the wind, therefore sailboats and boards sail at an angle so that the wind is able to fill the sail and create a difference in air pressure on either side which causes lift (Figure 1.1). The lift that is created causes sideways motion as well as forwards, the sideways motion is countered by a board or fin positioned centrally on the underside of the boat/board. Without this it would be impossible to sail in a straight line without drifting (RYA, 2016). Sailors are able to sail as close as 40° to the direction of the wind which gives performance benefit as less distance is needed to be covered as they zig-zag upwind. While it may be preferential to sail as close to the wind as possible to minimise the total distance covered, however some faster boats and windsurf boards can be sailed at greater angles to the wind so that they are able to travel faster and reduce the amount of turns across the wind called 'tacking' which requires decreasing in speed or almost stopping in some classes (Evans, 2009).

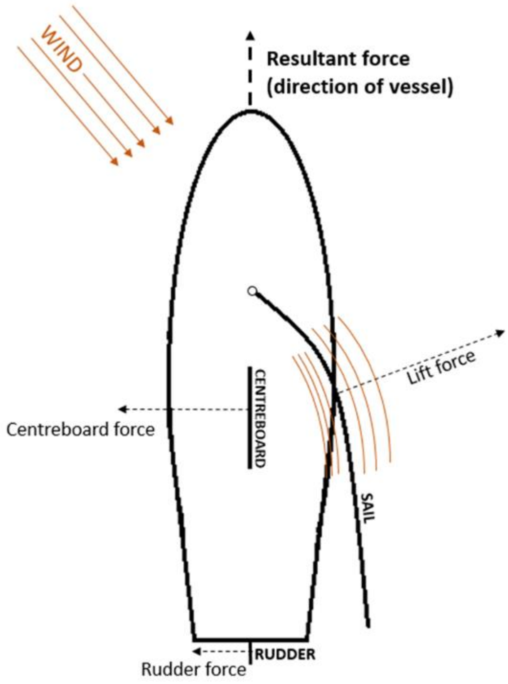

Figure 1.1 Force vector diagram of vessel in the water from above. Note spacing of wind on either side of sail which creates pressure differential and therefore lift force

As sideways motion results in sailing greater distances due to drifting, it is the aim that in the majority of classes that the boat/board is kept as flat as possible in the water so that the centreboard or fin is able to exert greater force. When wind speed increases the force exerted by the sail exceeds the force of the centreboard/fin, therefore the sailor (s) must contribute to keep the boat/board flat which will result in greater boat speed (Evans, 2009). When observing the rotational forces acting on a boat (Figure 1.2) it is evident that the sailor (s) must create a righting moment to counter the heeling moment of the sail by extending the body outside of the side of the boat.

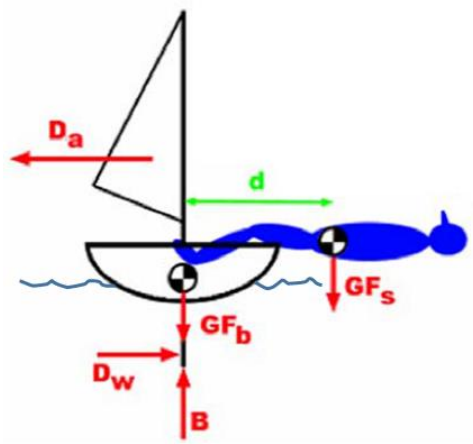

Figure 1.2 Force vector diagram of a single-handed dinghy in the water sailing upwind from behind. Note: D - Force, GF - gravitational force, B - buoyancy force, d – distance, a - air, s - sailor, b - boat, w – water. Adapted from Tan *et al.* (2006).

Hiking is generally accepted as the most physically demanding movement in sailboat racing (Spurway, 2007). The body is extended out of the side of the boat, anchored with the fronts of the ankles against a strap that runs along the centreline of the boat and the hamstrings against the side of the boat. This is combined with repeatedly pulling on the rope that controls the power of the main sail termed 'sheeting'. As wind speed increases there is a greater demand exerted on the sailor to harness the power of the sails and keep the boat flat resulting in greater boat speed (Mackie *et al.,* 1999). Some double-handed positions use a different method to counteract the heeling moment called trapeezing, where the whole body is extended out from the side of the boat with the use of harness which is attached to the mast (Besier and Sanders, 1999). Intensity is increased greatly as sailors hoist and drop the large spinnaker sail (Bay and Larsson, 2013) and are able to pump the sail using their whole body which fans the sail and increases boat speed (Besier and Sanders, 1999). This actions of hiking and trapeezing in sailboat racing are shown in Figure 1.3.

Figure 1.3 Images of Hiking (left) and Trapeezing (right). Note: Trapeezing sailor is the closest sailor on the right image.

Boardsailing is competed on Windsurf boards (Figure 1.4) and are governed by the same forces displayed in Figure 1.2, however to add speed sailors pump the sail which increases the physiological loading (Bojsen-Möller *et al.,* 2014). This movement becomes crucial in lower wind ranges, as due to the low weight of the rig and board combined relative to the sailor, this becomes the main driver of forward propulsion.

Figure 1.4 Image of boardsailing pumping

1.3.2 Sailing downwind

Sailing downwind in general is understood to be less strenuous as the heeling moment of the sail is reduced which reduces the physical cost (DeVito *et al.*, 1996). The sail is held further from the centreline to harness more wind from behind. The boat becomes more unstable which confirms the requirement for agility and balance (Bojsen-Möller *et al.*, 2014) as the risks of capsizing are increased, especially during manoeuvres when crossing the line of the wind (gybing). Intensity is increased when sailing downwind as sailors are able to use their body to rock and steer the boat and pump the sail to increase boat speed.

The other major component of forward propulsion which needs to be considered is drag which when the shape and mass of the boats/boards and equipment are equal is related to the body mass of the sailor (s) on board. If there is greater mass, the boat/board will displace more water which increases drag and slows it down, therefore there is a trade-off between having greater mass to increase righting moment upwind versus being heavier and displacing more water especially downwind (Evans, 2009). In all sailing classes the effect of body mass can have dramatic effects on boat speed and therefore performance in racing, the impact is class and position-specific (Bojsen-Möller *et al.*, 2014).

1.4 Olympic sailing

Sailing has been a planned part of the modern Olympic Games since its inception in 1896, although it was not staged in 1986 or 1904 due to inclement weather and the lack of an appropriate setting respectively. Women have competed alongside men since 1900, with the introduction of specific single-sex classes for females in the 470 class at the Seoul Games in 1988. Olympic sailing consisted of sailboats, up to 1980 where it was decided to introduce a Boardsailing event which has been present since 1984. Sailing at the Olympic Games has varied from three to 14 events (International Olympic Committee, 2011), with ten events competed in the most recent edition in Rio in 2016 (see Table 1.1).

Table 1.1 Sailing events in the Rio 2016 Olympics.

Class	Type of vessel	Gender
a) Laser Radial	Dinghy	Female
b) Laser	Dinghy	Male
c) RS:X 9.5m (b)	Windsurf board	Male
d) RS:X 8.5m (b)	Windsurf board	Female
e) Finn	Heavyweight dinghy	Male
f) 470 (2)	Dinghy	Male/Female
g) 49er FX (2)	Skiff	Female
h) 49er (2)	Skiff	Male
i) Nacra-17 (2)	Catamaran	Mixed

Note: (2) Denotes double-handed class, (b) boardsailing class.

Letter prefix relates to pictures in Figure 1.5

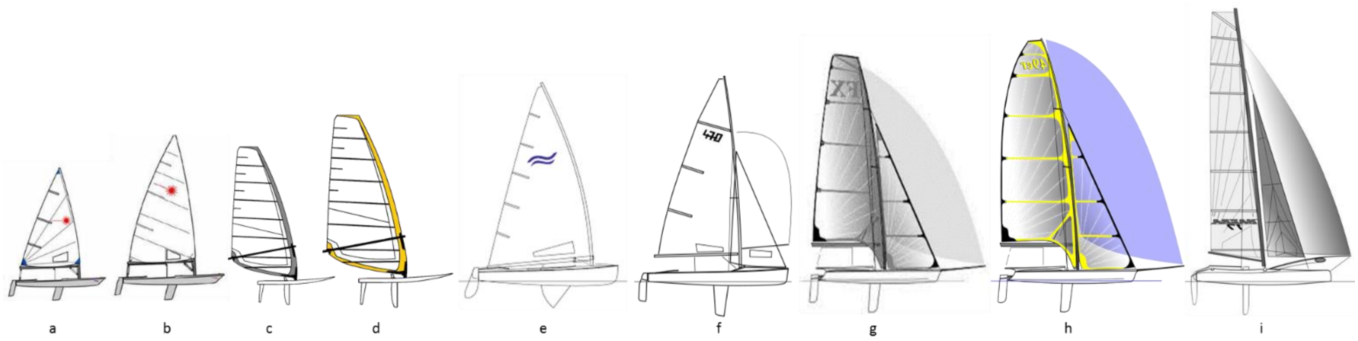

Figure 1.5 Sailing classes in Rio 2016 Olympics in mast height order. Note: a - Laser Radial, b - Laser, c - RS:X 8.5m, d - RS:X 9.5m, e - Finn, f - 470, g - 49er FX, h - 49er, i – Nacra-17

At the Rio 2016 Olympic Games nine classes were raced, with the 470 raced with a male and female crew separately which brings the total up to ten events. This comprised of three single-handed, two boardsailing, and four double-handed classes. At this level of competition all the classes have at least a moderate level of physicality, up to the RS:X 9.5m and Finn classes that are the hardest physically in the sport (Bojsen-Möller *et al.,* 2014), with boardsailing being compared to the demands of other Olympic sports such as cycling or rowing (Vogiatzis and De Vito, 2014). Class hulls and boards at the Olympic level are designed to maximise speed which increases the physical demand, plus the greater sail areas result in greater effort for the sailors to keep the boats flat through hiking and trapeezing and for the boardsailors to pump which will make them go faster.

The classes sailed in the Olympic Games are not fixed, therefore it is possible for new classes to be brought in for each four-year cycle. From London 2012 to Rio 2016 Games, there were two changes, with the Elliot 6m and Star being replaced by faster and more agile boats (49er FX and Nacra-17). At the time of completion of this thesis the exact classes that will be sailed in Tokyo at the 2020 Games is unknown. As can be seen in Figure 1.6 the movements involved in classes have changed, Bojsen-Möller *et al.* (2014) categorised the Olympic sailing classes into movements that are used and tracked these in Olympic Games from 1968 to 2016. Which evidenced the trend of sailing classes becoming faster requiring more physicality demonstrated by the reduction in side-hiking and increase in trapeezing. Additional to the trend for higher intensity boats, is the development of shorter races that involve more manoeuvres and reduced rest periods between races. Theatre-style racing, especially for medal races is being phased in which brings sailing closer to the shore which makes it more accessible than in previous Games, though it makes sailing conditions more difficult to judge due to the effect of topography and buildings on the land.

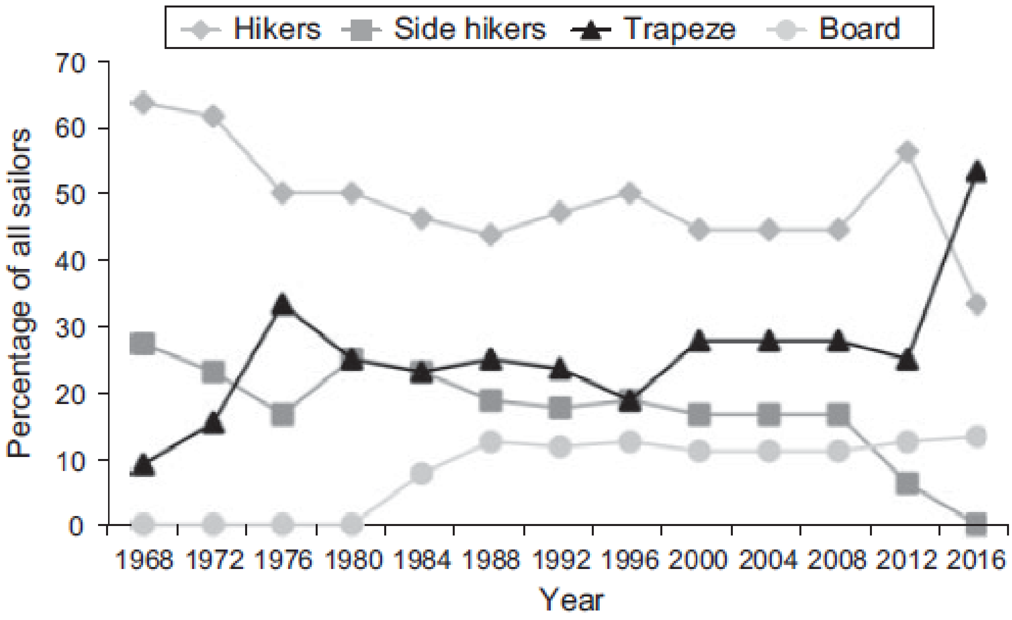

Figure 1.6 Changes to classes sailed at the Olympic Games from 1968 to 2016 categorised by Bojsen-Möller *et al*. (2015) into Hikers, Side-Hikers, Trapeze and Boardsailors. Note the shift from 2008 with Trapeze and Hiking classes.

1.5 Sailing racing

Sailing racing takes part in a regatta or racing series, where a pre-determined number of races are completed on an area of water identified using inflatable buoys and selected vessels where a race committee would stand. A racing series is won by the sailor with the lowest total cumulative score after the last race. Points are awarded as follows: 1st place = 1 point, 2nd place = 2 points, 3rd place = 3 points and so-on. The time it takes to complete the course is not key to winning as this is purely related to finishing positions, which can make racing extremely tactical. After a set number of races, depending on published sailing instructions, sailors are able to discard their worst score. In Olympic class racing it is common place for a series to end with a double-points 'medal race', where the top ten finishers race one final time where all scoring points are doubled. The potential for change in positions is therefore increased with two to 20 points on offer, therefore it is imperative for sailors to reach the medal race in good physical and mental condition.

Racing takes place within a guideline range of wind strengths from five to 30 knots (5.75 to 34.52 miles·hour^{-1}) to ensure a good quality of racing and sailor safety, with the risk of capsize increasing in higher winds. Sailors must complete the set course racing around marks (buoys) in particular order. All races start across an imaginary start line between a committee boat and a buoy which is set as perpendicular to the wind direction as possible.

Course lengths are judged by the race committee and calculated using pre-determined charts based on upwind, downwind and reach boat speeds in different wind strengths per class. Depending on class and level, sailors can expect to complete up to four x 25-60 min races a day and be on the water for around three – eight hours including getting to the race course and back from the shore.

A representative diagram of a typical Laser sailing a typical course is shown below in Figure 1.7. As a relatively slow boat, the Laser will tend to sail as straight a line as possible while 'running' downwind to ensure they sail the shortest distance possible. Faster boats may sail further distances as their sail set-up enables them to increase boat speed with greater angles, therefore it may look more similar to 'beating' upwind in the zig-zag pattern.

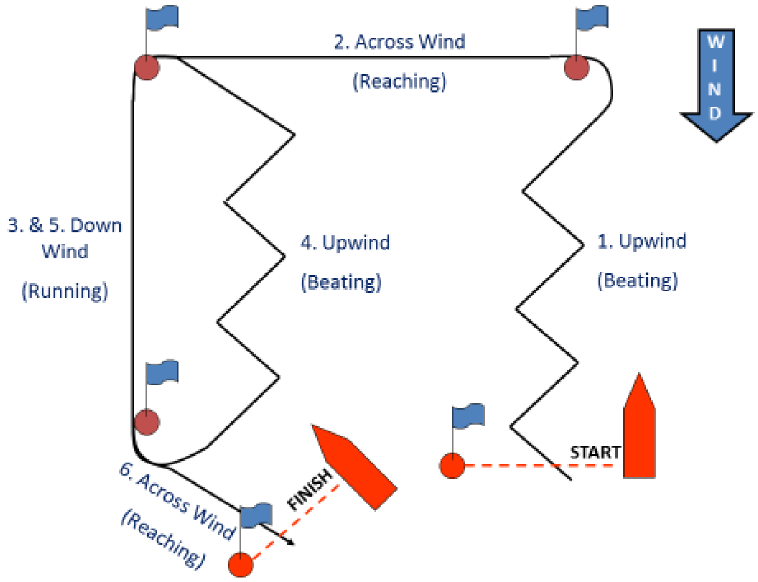

Figure 1.7 A diagram of a Laser sailing a typical Trapezoid Outer loop course

1.6 Pathway sailing

At Junior level there are six recognised classes within the Olympic pathway: three single-handed, one boardsailing, and two double-handed. Sailing at Junior level is typically not greatly physically demanding due to the power created by the smaller sail area and hull/board design limits speed. The exception may be the Laser 4.7 which is seen as a more demanding class than the Optimist and Topper (Callewaert *et al.,* 2014b), the Bic Techno 293 Windsurf boards in comparison to the dinghies and skiffs are hypothesised to the hardest class to sail physically at Junior level due to fact that sailors need to use their body mass to pump the sail in light to moderate winds similar to the comparison of hiking and trapeezing classes versus boardsailing at Olympic level (Bojsen-Möller *et al.,* 2015). The main development at Junior level is to progress 'race craft' which comprises of tactics, strategy, sailing knowledge and feel.

When sailors make the transition from Junior to Youth classes, the level of physical demand increases (Bojsen-Möller *et al.,* 2007; Callewaert *et al.,* 2014b). Sailing classes are designed for higher performance and have greater sail areas to harness the power of the wind and therefore go faster. Youth level sailing consists of: two single-handed, one boardsailing and three double-handed classes. At Youth level females begin to sail the same single-handed classes that are raced at Olympic level (Laser Radial and RS:X 8.5m), male single-handed Youth sailors begin with sailing the same class as the females though progress on to the male Olympic class when they become physically able, which usually occurs around 17-18 years old. These classes become physically challenging where larger amounts of strength and aerobic fitness are required to sail fast and to maintain performance through a whole regatta that may consist of 12-15 races over 5-6 days (Bojsen-Möller *et al.,* 2014). The 29er and Spitfire are the fastest boats in the Youth programme only surpassed by the RS:X 8.5m, the Youth boardsailing class, which is the same as the female Olympic event. Olympic pathway classes are summarised in Table 1.2.

Table 1.2 Sailing classes in the Olympic pathway below Olympic level.

Class	Level of pathway	Type of vessel	Gender
a) Optimist	Junior	Dinghy	Male/Female
b) Topper	Junior	Dinghy	Male/Female
c) Laser 4.7	Junior	Dinghy	Male/Female
d) Bic Techno 293	Junior	Windsurf board	Male/Female
e) Cadet (2)	Junior	Dinghy	Male/Female/Mixed
f) RS Feva (2)	Junior	Dinghy	Male/Female/Mixed
g) Laser Radial	Youth	Dinghy	Male/Female
h) Laser	Youth	Dinghy	Male
i) RS:X 8.5m (b)	Youth	Windsurf board	Male/Female
j) 29er (2)	Youth	Skiff	Male/Female
k) 420 (2)	Youth	Dinghy	Male/Female
l) Spitfire (2)	Youth	Catamaran	Male/Female/Mixed

Note: (2) denotes double-handed class, (b) boardsailing class, letter prefix relates to pictures displayed in Figure 1.8.

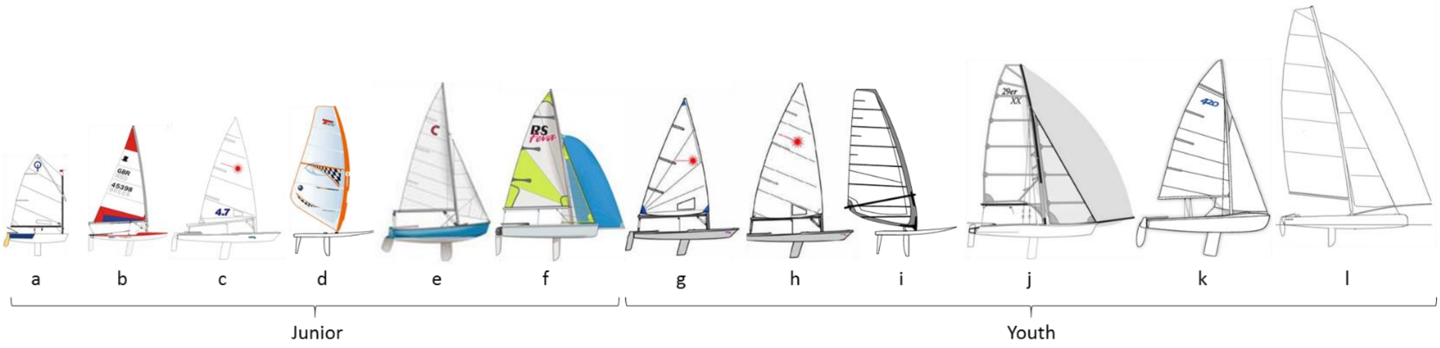

Figure 1.8 Sailing classes in Olympic pathway below Olympic level. Note: a - Optimist, b - Topper, c - Laser 4.7, d - Bic Techno 293, e - Cadet, f - RS Feva, g - Laser Radial, h - Laser, i - RS:X 8.5, j - 29er, k - 420, l - Spitfire.

1.7 Olympic pathway

The ultimate aim of the Olympic pathway is to constantly deliver sailors to win medals at Olympic Games. The pathway that a sailor may travel is shown in Figure 1.9 which highlights the possibility of a 12 – 20 year journey from taking up the sport to winning Olympic gold. A number of UK-run squads exist with sailors as young as six years old, with the purpose of delivering sailors up the Olympic pathway arming them with the skills and behaviours required of achieving success at the highest level. For more detail on pathway sailing classes see Appendix 1 – Olympic pathway sailing classes.

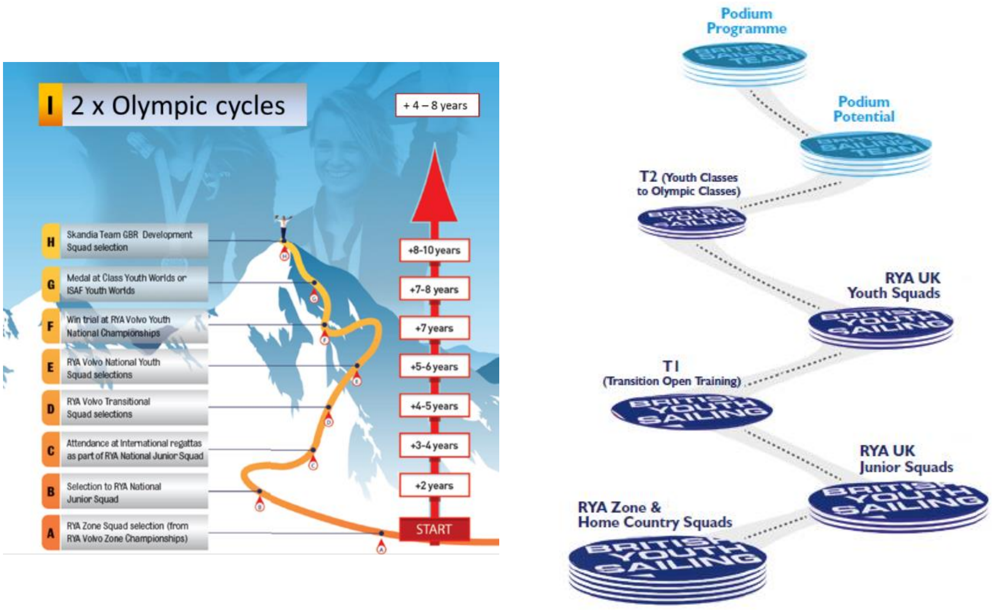

Figure 1.9 Structured path of development through the British Sailing Team Olympic pathway (RYA Pathway to Podium Handbook, 2014)

The trajectory of sailors through the Olympic pathway can be complex (Figure 1.10) where a number of different classes will be sailed at various levels. The RYA supports participation and competition in a set number of classes at specific levels that are typically age-grouped, although there is the ability to move outside of age due to physical or technical development. It is common for sailors to participate and compete in a number of different classes at the same time outside of the UK-run squads, or to drop in and out of the pathway.

All classes within the Olympic pathway require different skills and physical abilities to sail (Bojsen-Möller *et al.,* 2007; Bojsen-Möller *et al.,* 2014), ranging from slow single-handed dinghies to fast/agile double-handed skiffs, catamarans and windsurf boards. Therefore with the possibility of sailing different classes through the pathway that have different demands, added to the potential change in Olympic classes every four years it is key that sailors are developed with that aim in mind. In the recent lead up to the Rio 2016 Olympic Games a number of Great British sailors changed classes from hiking to trapeezing movements, highlighting the need for high levels of ability across a range of physical competencies.

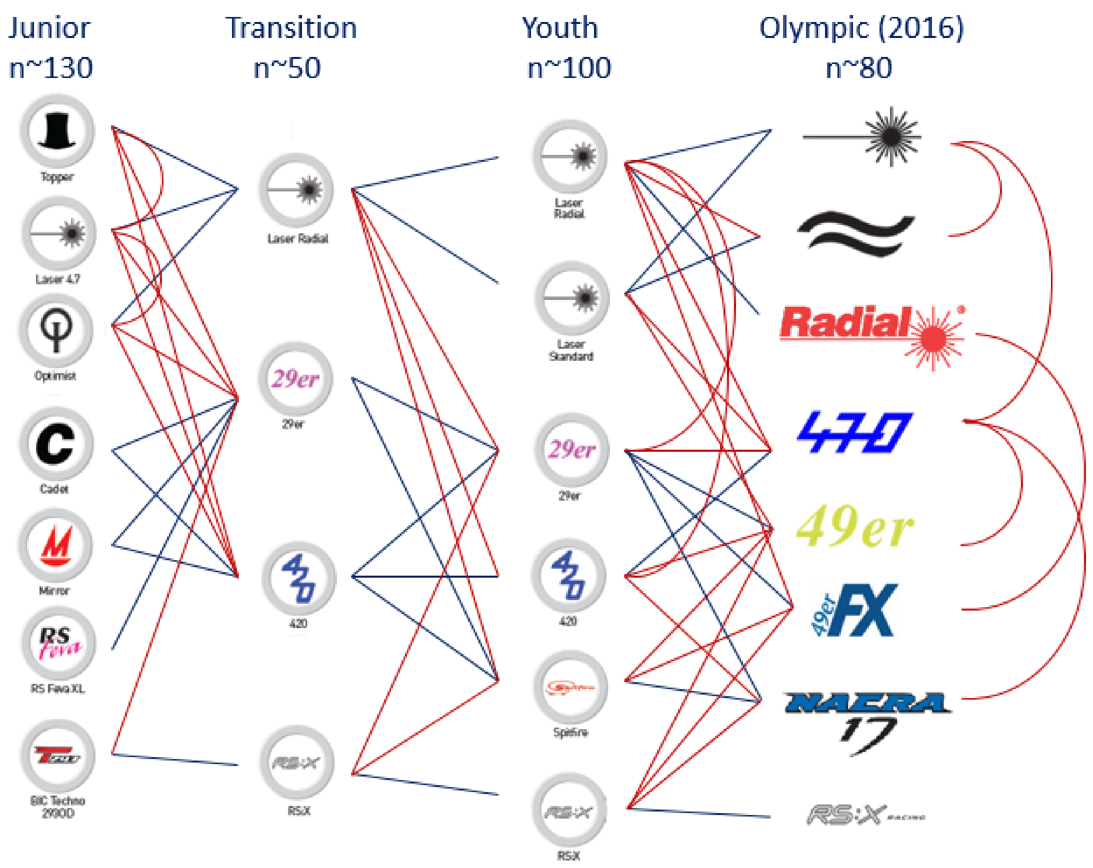

Figure 1.10 Theoretical developmental paths through the British Sailing Team Olympic pathway classes. Note: Dark blue lines denote most likely trajectory i.e. sailors remaining in single or double-handed classes, red lines denote other possible trajectories previously witnessed, notably changes observed at Podium level

1.8 Aim of thesis

The variation evident in sailing adds a unique complexity to the developmental journey; consisting of a range of demands across classes and positions, with different potential trajectories within these classes towards a changeable set of Olympic classes once sailors reach senior level. This thesis will focus on physical development which is relevant as Olympic sailing is observed as becoming more competitive and physically demanding in recent cycles (Bojsen-Möller *et al.*, 2014). Providing sailing-specific physical data through development adds objectivity to the subjective skill assessment of coaches, and results which may be influenced by environmental conditions. The relative importance of attainment in all aspects within a profile may not be equal consistently through development (Williams *et al.*, 2008), though sailors will need to develop physically to meet the demands of any class they sail, suggesting a minimum level of competency to be required to optimise development/performance as put forward by Vaeyens and colleagues (2008).

The creation of the dual research-applied post of the lead researcher between the British Sailing Team and the University of Chichester was to develop on current practice within the physical preparation of sailors, and to improve the robustness of the profiling process within the Olympic pathway. This would be achieved by initiating a longitudinal process of monitoring sailors, spanning further than the time course of the PhD research to further understand the transition to elite senior success. Due to the dearth of research in Youth sailing, this thesis will aim to improve the understanding of Olympic pathway sailing, confirming the key physical characteristics of development and develop the robustness of the physical profiling process. It is proposed that physical profiling assessed relative to sailing-specific benchmarks would be of optimal use for monitoring development and supporting the progression of sailors within the Olympic pathway.

Chapter 2 Literature Review

2.1 Introduction

The purpose of this chapter is to review current perspectives in talent research, understand the relationship of physical characteristics and talent development, and present the literature to date reporting the physical requirements of Olympic and elite Junior and Youth sailing. Throughout this thesis athletes and sports players of different performance level and age will be described by the following classification using the terminology from Rees *et al.* (2016): elite to non-elite to refers to the boundary of athletes competing at or below national level; Junior, Youth and Senior refers to athletes who are under 16 years, between 16 and 18 years and over 18 years old respectively. Super-elite is reserved to athletes who are serial Gold medallists at World and/or Olympic level.

2.2 Talent

Elite international sport is becoming more competitive, with more countries winning an increasing share of Olympic and World Championship medals, alongside this increase in competitiveness, countries are increasing investment towards the acquisition of more medals (DeBosscher *et al.*, 2007; Rees *et al.*, 2016; Vaeyens *et al.*, 2009). Various examples are evident in recent history to support the notion that increased spending results in greater success, Hogan and Norton (2000) and DeBosscher *et al.* (2013b) identified strong correlations (r > 0.90) between success and the amount of expenditure on sporting programmes. Hogan and Norton (2000) measured the exact cost of success in the period from the 1976 and 1996 Olympics at AUS$37 million per gold medal and AUS$8 million per medal, with an increase in funding from AUS$1.2 million in 1976 to AUS$106 million in 1997/8, within this time frame Australia went from 32nd place winning no gold medals to 4th place winning 16 in Sydney 2000 (Olympic.org, n.d.). Similarly Great Britain went through a process of increased funding alongside a redistribution of National Lottery funding, and went from one gold and 15 medals in total in Atlanta 1996 Olympics, to 11 golds and a total of 28 medals in Sydney 2000 Olympics. This trajectory of increased success and funding for Great Britain has continued with £88 million pre-Athens 2004, to £235 million in Beijing 2008, £261 million for London 2012, and £355 million for Rio 2016 (Rees *et al.,* 2016).

It is clear that Sporting National Governing Bodies (NGBs), for example British Cycling or British Sailing benefit from sporting success with increased funding, and this continues to the athletes. A notable example is Sir Chris Hoy, who is estimated to have earned approximately £24,000 a year before the Beijing 2008 Olympics from funding and sponsorship. As a result of his triple gold medal haul in Beijing he attracted a number of higher profile sponsors including Kellogg's, Harrods and Adidas, and had estimated wealth of over £2 million (Independent, 2012). Using role models such as Sir Chris Hoy, governments attempt to justify the great amount of public money invested into elite sport through a number of benefits including an increase in the health of the nation from resultant mass sporting participation and physical activity, improved national identity and pride and international kudos in world political stage – this increase in sporting investment has been termed a 'global sporting arms race' (DeBosscher *et al.*, 2007; DeBosscher *et al.*, 2013b; Houlihan and Green, 2008; Wicker *et al.*, 2012).

As a result of this increased competitiveness and financial pressure to obtain medals, NGBs are investing into maintaining a steady stream of athletes who are able to produce success at the highest level (Vaeyens *et al.*, 2009). Their aim is to establish a framework that paves a pathway to international success that systematically identifies and develops exceptionally gifted young athletes, so that resources are focused on athletes with the greatest potential (Abernathy, 2008). Examples of these resources include: more competition/training opportunities, access to performance lifestyle and other support services, a higher level of coaching and funding (Vaeyens *et al.,* 2009). There is an assumption that provision of these resources will increase the probability of success, though it must be noted that there are a number of interlinking factors that affect the progression of future international sports medallists, including intrinsic (anthropometry, rate of maturation, adaptation to training, coachability, motivation and other psychological skills) and extrinsic factors (family, coach, access and opportunity and education) (Bergeron *et al.*, 2015). This has led to a difference of opinion in to the effectiveness of such talent pathways which will be discussed later in this thesis.

One of the difficulties when it comes to the concept of 'talent', is the lack of consensus when it comes to defining talent, with the term being used to define both the start and the end of a development process (Gagné, 2004). The Collins online dictionary states that talent is "an innate ability, aptitude or faculty…above average ability" (Collins, n.d.) which implies that talent is genetically endowed, which has been questioned by a number of researchers (Ericsson *et al.,* 1993; Gagné, 2004; Howe *et al.*, 1998; Tucker and Collins, 2012). Howe *et al.* (1998) listed characteristics of talent:

1. Originates in genetics and is partially innate
2. The full extent may not be witnessed in the early stages though there will be indicators
3. These indicators may be used as a base for predicting future success
4. Talent is restricted to a small percentage of a population
5. Talents are specific to the domain in which it is measured

Howe and colleagues' characteristics provide a step forward in the understanding of talent with it being more complex than an over simplistic dictionary definition. Defining talent may involve viewing the concept from a social perspective, as talent can be confirmed relative to the value that is placed on it via the subculture in which it exists (Tranckle and Cushion, 2006). Gagné (2004) differentiated the terminology of being talented from being 'gifted' and sought to cut through the vagueness of talent through defining it as an individual placing in the top 10% of active peers of a similar age from outstanding mastery of systematically developed skills and knowledge. This definition moves away from the dictionary definition and does not account for a non-linear trajectory of talent development as an athlete falling out of the top 10% would cease to be regarded as talented, discounting the natural variability in the progress of developing elite athletes (Gulbin *et al.,* 2013; Rees *et al.,* 2016; Vaeyens *et al.,* 2009;). One of the main criticisms of Gagné's model is that it was developed in an educational setting which is inherently different from developing sporting success.

While the definition of talent remains debated, the process of the pathway to elite success is more accepted. Williams and Reilly (2000) presented a framework from their earlier work (Williams and Franks, 1998) with distinct stages of Detection, Identification, Development and Selection (p.659) and these definitions will be used in the thesis:

Talent Detection: "Discovery of potential performers who are currently not involved in the sport in question"

Talent Identification: "Process of recognising current participants with the potential to become elite players [athletes]"

Talent Development: “Players [athletes] are provided with a suitable learning environment to realise their potential”

Talent Selection: “On-going process of identifying players at various stages who demonstrate prerequisite levels of performance for inclusion in a given squad or team”

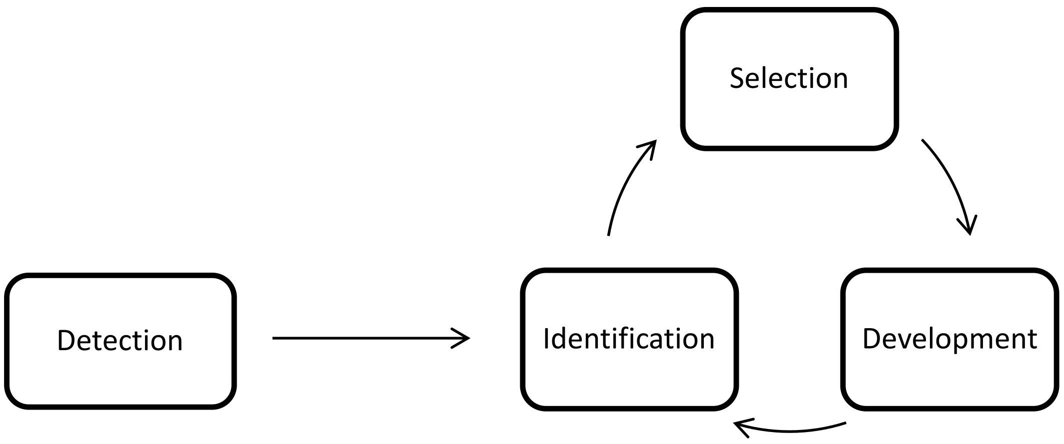

Figure 2.1 Stages within the development of talent (Williams and Franks, 1998; redrawn from Williams and Reilly, 2000)

It is clear that the concept of talent is complex. As the research in this thesis investigates the development of sailors within the Olympic pathway who have already been identified as ‘talented’, this literature review will focus more on the process cycle of Identification-Development and Selection.

2.3 Talent Identification

Williams and Franks’ (1998) definitions in the previous section included Talent identification (TID), which described the ability of a process to identify participants with the potential to progress to be elite adult athletes. This has been the focus of a number of national governing bodies and professional teams since the 1950’s (Regnier *et al.,* 1993). The majority of TID pathways select ‘talented’ athletes based on current competitive results, most likely due to pressure on resources and financial costs (Vaeyens *et al.,* 2009). The bases of ‘traditional’ models of talent pathways focus on the assumptions that the elite athlete journey is linear, involving single-sport participation, earlier success and participation will increase the likelihood of success into adulthood, and that success is more probable from increased training and competition (Güllich and Emrich, 2006) linked closely with the now challenged models of early specialisation and deliberate practice (Ericsson *et al.* (1993).

The process of predicting elite adult participation/success, especially at younger ages, has been challenged by a number of researchers (Abbott and Collins, 2004; MacNamara and Collins, 2011; Pearson *et al.,* 2006; Suppiah *et al.,* 2015; Vaeyens *et al.*, 2008; Vaeyens *et al.,* 2009). Vaeyens *et al.* (2009) stated that there was no empirical support for the traditional approach to TID. When investigating the literature on the prediction of elite adult participation from elite Junior and/or Youth participation the results are varied, with the majority stating elite Junior and Youth athletes have odds significantly less than the flip of a coin of reaching elite adult status (Table 2.1). Resource and financially driven models will ultimately have to decrease the amount of numbers within higher levels of performance as the requirement for support will increase, producing a natural drop off in 'talented' athletes which may partially explain the poor conversion rates observed (Abbott *et al.,* 2002). Though it is important to note that the measure of success within a pathway varies, for example in gymnastics success would be characterised by production of just two world class athletes a year (Pion *et al.*, 2016) so the question to ask is whether talent drop-off is a significant issue in all sports?

Table 2.1 Summary of prediction percentage in athletes progressing from Junior to Adult Elite participation

Study	Sport	Age	Sample	% prediction	Level Attained
Robertson *et al.* (2014)	Australian Football (AFL)	U18	N = 3,846 (Applied for National state championships teams)	6%	Drafted to Professional AFL
Schumacher *et al.* (2006)	Cycling	U18	N = 4,432 (Participants in Junior World Championships)	29.4 / 34.6%	Elite adult cyclist, (retrospective/ prospective)
Barreiros *et al.* (2014)	Football, Volleyball, Swimming and Judo	U14 – U16	N = 289 (National level athletes)	34.6%	Elite adult participation
Till et al. (2014)	Rugby League	U14 – U16	N = 580 (Talent ID group)	12 / 57%	Super League Professional/ Academy
LeGall *et al.* (2010)	Football	U14 – U16	N = 161 (Pre-apprentice at National Institute)	10 / 35%	International/ Professional
Ostojic *et al.* (2014)	Football	U14	N = 48 (Serbian Top Division)	33%	Participating in top European leagues/ International
Pion *et al.* (2016)	Gymnastics	U8	N = 243 (Top national athletes)	14%	Maintained elite status 5 years later

A number of studies have investigated a range of sports that challenge the conception of successful athletes following elite linear single-sport journeys to elite adult level (Gulbin *et al.*, 2013; Güllich and Emrich, 2012; Güllich and Emrich, 2014). Gulbin and colleagues (2013) analysed the patterns of performance development of 256 elite athletes across junior and senior competitive experience in a mixture of sports which they categorised as cgs (results measured in centimetres, grams or seconds) and non-cgs sports. Less than 7% of athletes experienced a 'pure' linear trajectory from Junior to Senior performance, with 83.6% experiencing either mixed ascent or decent trajectories containing concurrent experience or multiple crossovers of playing level. The ages of first competitive experience varied widely between athletes from approximately 9.1 years old (78.1% of athletes), to approximately 14.3 years (17%) and approximately 15.6 years (4.3%). A selection of 'late bloomers' averaged the first competitive experience within their main sport at approximately 20.7 years, these athletes were noted specifically for their participation in other sports in pre-elite or elite level (52%). Güllich and Emrich's (2012) study investigated the career paths of 4,686 successful senior athletes through elite support programmes in Germany. Interestingly early entry into a TID pathway was very strongly correlated to early exit ($r = 0.92$), higher levels of squad status was related to a later age of first selection with mean age of A and B high performance squad members (19.2 ± 2.7 years). Annual squad turnover was 44%, successful elite adult athletes typically experienced multiple de-selection and re-selections on the pathway to success, with the majority of Olympians experiencing discontinuation in squads in the four years prior to the Games (57%). In conclusion there was no single trajectory experienced by successful elite adult athletes. Gray and Plucker (2010) state that athletes who survive this process of de-selection and selection, and therefore learn to cope with disappointment and how to overcome these traumas will likely grow stronger intrinsic motivation and grit aiding the ability to progress successfully.

The ability of TID to predict future elite adult success is difficult, as highlighted by Suppiah *et al.* (2015) who state that anticipating future success is a science and an art, based on a variety of intrinsic and extrinsic factors which are often individual, immeasurable and impossible to recreate. It is therefore a risk of using mono-disciplinary models of TID that discount the multi-factorial interactions and compensations that athletes may experience (MacNamara and Collins, 2011). Vaeyens *et al.* (2008) cite a range of factors for the reason behind failure to accurately predict future success: the lack of scientific grounding, elite qualities may only evolve at later ages, similar factors are considered important in Youth athletes as in elite adult athletes, the individual nature of maturation. A main challenge to TID models is the lack of a longitudinal approach, typically using one-off snapshots of ability which increases the risk of missing key attributes of developing elites that are yet to evolve (Abbott and Collins, 2004).

2.3.1 Predicting elite progression based on physical characteristics

In an attempt to gain more understanding of young athletes' potential within TID models, sport programmes and professional teams have included the assessment of a number of characteristics including physical, psychological and sociological (Lidor *et al.,* 2009). This thesis focuses on physical characteristics of physiological (e.g. aerobic fitness, strength and speed), motor (e.g. balance, co-ordination, and agility) and anthropometrical (height, body mass and body composition). Measuring physical characteristics may aid the prediction of elite adult success by adding a battery of tests that provides objective scientific data to work alongside the subjective coach assessment of current ability and/or potential (Abbott *et al.,* 2002). Bompa and Haff (2009) state the benefits of using scientific criteria in TID are the following: reduces the time to reach elite level by selecting those gifted in the sport, reduces the workload of the coach so they can focus on training superior athletes, increases competitiveness and promotes a more stronger group of athletes, knowledge of enhanced abilities increases an athlete's confidence, aids the intervention of support staff to accelerate development.

Obtaining physical data from TID athletes may provide programmes and sports with relevant information of athletic potential, not just of developing technical sporting talent (Williams and Reilly, 2000). The ability of an individual to display physical skills and physiological attributes opposed to current level of attainment may add a level of aptitude to help inform the TID process (Abbott *et al.,* 2002). Once this data has been collected it will help support staff establish normative values for athletes, help inform training prescription and monitor progress (Lidor *et al.*, 2009). The ability of physical characteristics to impact future performance is varied across different sports which is not surprising due to the fact sports require different contributions from physical attributes (Falk *et al.,* 2004; LeGall *et al.,* 2010; Robertson *et al.,* 2014).

Table 2.2 Physical Testing and future elite progression (*P* < 0.05 unless otherwise stated).

Study	Sport	Age	Sample	Future Level	Selected Test Items	Main results
Robertson *et al.* (2014)	Australian Football (AFL)	U18	N = 3,846 (Applied for National state championships teams)	Professional AFL/ National State Champs/ State	Anthropometry, Lower body Power, Agility, Speed, Aerobic Capacity	• Aero, height and Speed most influential (62–64%) • Small to Moderate effect size of physical measures in Pro and National vs. state (*d* = 0.2 – 0.71) • Trivial to small of Pro to National (*d* = 0.05 – 0.4)
Till *et al.* (2014)	Rugby League	U14 – U16	N = 580 (Talent ID group)	Professional/ Academy/ Amateur	Anthropometry (including Body composition), LB Power, Speed, Agility, Aerobic capacity	• Pro ↑ Am on Body comp, LB Power and Speed • No diff between Pro and Acad
Till *et al.* (2016)	Rugby League	U14, U15, U16	N = 580 (Talent ID group split into U14, U15 and U16)	Professional/ Academy/ Amateur	Anthropometry (including Body composition), LB Power, Speed, Agility, Aerobic capacity	• U14 No diff • U15 Pro ↑ Am on Body comp, Speed, Agility, Aero ($\eta^2 = 0.16$) • U16 Pro ↑ Am on Body comp and Agility ($\eta^2 = 0.12$) • U16 Pro ↑ Acad and Am on Aero

LeGall *et al.* (2010)	Football	U14 – U16	N = 161 (Pre-apprentice at National Institute)	International / Professional/ Amateur	Anthropometry, LB Power, Speed, LB Strength, Aerobic capacity, Anaerobic power	• Pro ↑ Am on Body mass (*d* = 0.56) • Int and Pro ↑ Am in height (*d* = 0.85, *P* < 0.01) and Anaerobic power (*d* = 0.79, *P* < 0.01) • Int ↑ Am in LB Power (d = 0.53) and Speed (*d* = 0.50) • No diff Int vs Pro but ↑ trend in 9/14 tests
Gonaus and Müller (2012)	Football	U15 – U18	N = 1,365 (National Academy)	International U18-U21/ Non-international	LB and UB Power, Speed, Agility, Flexibility, Repeated Sprint, Aerobic capacity, Co-ordination	• ↑ in Int (Power, Speed, Flex, Co-Ord, Aero) • U15 UB Power + RSA + Agility = 63.4% • U16 and U17 UB Power + RSA + Aero = 62.7 and 63.6% • U18 UB Power + RSA + Co-Ord = 66.2% • RSA (η^2 = 0.07 – 0.09), Speed (η^2 = 0.04 – 0.05), UB Power (η^2 = 0.05 – 0.11)
Falk *et al.* (2004)	Water Polo	U13 – U15	N = 24 (Selection for national team)	Youth National/ Non-Youth National	Swim sprint, Swim endurance, LB Power	• ↑ in Physical tests predicted 67% of Junior national team two years later with 8/11 going on to Senior national team

Note: Aero = Aerobic capacity, LB/UB = Lower/Upper Body, Body comp = Body Composition, RSA = Repeated Sprint Ability, Flex = Flexibility, Co-Ord = Co-Ordination, Pro = Professional, η^2 – effect size (small effect 0.01, medium 0.06, large 0.14), *d* – Hedge's effect size (small effect 0.2, medium 0.5, large 0.8)

The studies covered in Table 2.2 found that physical characteristics were able to differentiate between future elite versus amateur participation levels, although the majority revealed less than moderate effect sizes and fewer differences were observed between elite and sub-elite level (e.g. Professional vs. Academy). It is important to note that the effect sizes stated above do not imply that physical characteristics predict future performance, as the pathway to elite adult success is based on the contributions of many factors (Abbott *et al.,* 2002; MacNamara and Collins, 2011; Suppiah *et al.,* 2015; Vaeyens *et al.,* 2008) although improved physical attributes may support progression (Lidor *et al.,* 2009). The lack of a stronger effect has been hypothesised to be partly due to the discrete nature of physical testing within open skilled sports as they are far too removed from real sporting situations. This is compounded as physical testing is performed in a rested state typically on artificial or indoor surfaces that may not replicate the actual skills required in performance (Lidor *et al.,* 2009; Suppiah *et al.*, 2015).

2.3.2 Relationship between physical characteristics and sports performance

To further understand the TID process various authors have attempted to identify the physical characteristics that distinguish the performance level of young athletes (Pearson *et al.,* 2006). Matthys and colleagues (2013a) tracked elite and non-elite handball players in two different age groups (U14-U16 and U16–U18) for three years across a number of physical characteristics, with elites in both groups scoring higher in aerobic capacity, speed, repeated sprint ability (RSA) and co-ordination. The most discriminating factors were aerobic capacity (↑ 24 to 25%, $P < 0.01$) and co-ordination (↑ 8.9 to 14.8%, $P < 0.05$). However no differences were observed in improvement over the three years between performance levels or in any anthropometrical measurements after accounting for maturation status. Different anthropometrical characteristics were observed in top-elite, elite and non-elite groups of U17 female handball players (Moss *et al.,* 2015). Top elite players were found to be taller and heavier than elite and non-elite (~11 cm and 11 kg respectively), this coupled with increased lean body mass led researchers to conclude that top elite players had more functional (muscle) mass. This is reflected in the top elite players also having greater lower body power, speed, RSA and aerobic capacity ($P < 0.05$). Both authors cited the link between the key physical characteristics with linking to successful completion of the specific demands of the sport, this was also evident in another team invasion sport by Reilly *et al.* (2000) who found elite U17 football players outscored non-elites in 8/10 physical tests. Elite players were found to be leaner (All data in parentheses displayed as mean ± S.D. unless reported otherwise: 11.3 ± 2.1 vs. 13.9 ± 3.8% body fat, $P < 0.01$), less endomorphic (2.1 ± 0.5 vs. 2.9 ± 1.0, $P < 0.05$), had greater $\dot{V}O_{2max}$ (59.0 ± 1.7 vs. 55.5 ± 3.8 $mL \cdot kg^{-1} \cdot min^{-1}$) and greater lower body power measured by Standing Vertical Jump (55.80 ± 5.82 vs. 50.21 ± 7.58 cm, both $P < 0.05$). The most discriminating factors were speed at 15m (2.44 ± 0.07 vs. 2.56 ± 0.12 sec, standard coefficient = -2.35) and agility (7.78 ± 0.18 vs. 9.53 ± 0.73 sec, both $P < 0.01$) which were felt as key demands of match play. Mohamed *et al.* (2009) also found key differences in physical characteristics related to match play in handball as RSA and height were found to discriminate 87.2% of elite vs. non-elite U16 players, after accounting for maturation status elites also had improved body composition and arm to height ratio. Elite U16 players also possessed greater lower body power measured by standing long jump (SLJ) (218.7 ± 12.3 vs. 194.2 ± 21.2 cm), grip strength (46.4 ± 6.6 vs. 35.6 ± 11.0 kg), trunk endurance (sit-ups) (28.5 ± 4.2 vs. 25.5 ± 2.7 reps) and endurance shuttle run (10.3 ± 1.2 vs. 9.2 ± 1.4 min) (all $P < 0.01$ to 0.05).

Not all studies have found physical characteristics to differentiate performance levels, Franks *et al.* (1999) revealed no differences between U17 football players who were/were not drafted into professional contracts in anthropometry, body composition, aerobic/anaerobic capacity or speed. Both groups of players exhibited high levels of aerobic and anaerobic capacity, and differences were observed between playing positions. A similar result was found in U14 – U15 male and female hockey players (Elferink-Gemser *et al.,* 2004); no difference was observed in anthropometry, body composition, speed, RSA or aerobic capacity between performance levels, however elite players outscored non-elites in technical, tactical and psychological characteristics. The authors warned against the use of sport skill-based tests for TID that favour athletes who have experienced greater time in sport-specific training, as this may be representative of current ability/experience rather than potential for future progression. From these two studies it appears that physical testing may not be sensitive enough to discriminate between groups that differ in performance level that have been already identified as 'talented'.

A similar finding was exhibited in Vaeyens *et al.* (2006) investigation of U13 to U16 football players who were reported as 'elite' – top two divisions of national league, 'sub-elite' – third and fourth division and 'non-elite' – regional amateur players. Multiple MANCOVAs were performed with maturation status as the covariate revealing elite players could be discriminated against non-elites in speed, strength, flexibility, aerobic capacity and anaerobic power across all age groups. However when compared with sub-elites differences were less apparent, differences were found only at U15/U16 level in endurance shuttle run (10.8 ± 1.2 vs. 9.4 ± 1.4 and 11.2 ± 1.6 vs. 9.8 ± 1.0 min respectively), U15 in 300m shuttle tempo run test of anaerobic capacity (69.6 ± 3.5 vs. 73.3 ± 6.2 sec), and all speed-related tests at U16 level – 30m sprint and shuttle sprint (3.9 ± 0.2 vs. 4.0 ± 0.2 sec, 13.6 ± 1.0 vs. 14.2 ± 0.7 sec), suggesting that differences in these groups become greater as players enter late adolescence. The most discriminating factors between elite and non-elite players were running speed at U13 and U14 (4.4 ± 0.2 vs. 4.7 ± 0.2 sec and 4.3 ± 0.2 vs. 4.5 ± 0.3 sec respectively), and aerobic capacity at U15 and U16 level (10.8 ± 1.2 min vs. 8.7 ± 1.7 and 11.2 ± 1.6 vs. 9.3 ± 1.6 min respectively). Large inter-individual differences were found in this study, this combined with the significant effect of maturation status highlights the variability of adolescent athletes and the multi-factorial compensations in that may account for similar performance at Junior and Youth level (MacNamara and Collins, 2011).

The previous section revealed that physical characteristics have been shown to be able to discriminate players of elite vs. non-elite status of similar age groups in some, but not all studies and with varying magnitude. When investigators have analysed groups of different ages it appears that the discriminating physical attributes differ between age groups (Till *et al.,* 2013a; Vaeyens *et al.,* 2006). The following section will investigate how age or development level affects levels of physical attributes in elite athletes:

Lawton and colleagues (2012) investigated physical characteristics and 2,000m rowing ergometer performance in Youth (U18) vs. senior (18+ years) male and female elite heavyweight rowers. No anthropometrical difference was observed between groups for males, though after correcting for body composition and height senior females were heavier and had greater sitting height (P = 0.01 & 0.04). Youth rowers were found to be shorter and lighter than previous data on Olympic champions (males -6 cm and -9 kg, females -6 cm and -6 kg) revealing that both genders of youths in this study may not currently possess the characteristics required for top elite success. Faster 2,000m rowing ergometer performance (male senior vs. Junior: 366 ± 9.3 vs. 382 ± 5.0 sec, female: 411 ± 6.3 vs. 442 ± 8.5 sec) was explained by greater strength and endurance in both genders with effect sizes ranging from moderate to very large (0.9 – 1.9). The most differentiating physical performance factors were stated to be upper body pull strength and endurance measured using 5 and 120 repetition maximum (RM) tests using a Concept II dynamometer (5RM/120RM male senior vs. Junior: 617 ± 95 vs. 469 ± 60 J/ 339 ± 66 vs. 257 ± 28 J, female:

342 ± 54 vs. 267 ± 41 J/ 204 ± 46 vs. 153 ± 16 J). López-Plaza *et al.* (2016) observed positive relationships between anthropometry, upper and lower body power, flexibility and aerobic capacity (P < 0.01 – 0.05) with elite sprint kayak and canoe athletes of an average age of 13.7 years. When analysed further, age and maturation status were found to be the strongest predictors of on-water performance for canoe and kayak respectively. When maturity was accounted for all anthropometrical factors, apart from body composition, only flexibility and upper body power, differentiated the early and late maturers.

The effect of maturation status on physical characteristics was also established in a group of elite U16 and U17 football players (Vandendriessche *et al.,* 2012). The two groups were of similar age and then grouped further by maturation status confirmed using a prediction for age at peak height velocity (APHV) (Mirwald *et al.,* 2002), earlier maturing players were taller and heavier (P < 0.001) in both groups. U16 early maturers outscored their peers in the majority of fitness tests: grip strength, lower body power, agility and speed, though not in flexibility or starting speed (5 m sprint), similar improved scores in the more mature group were observed in the U17 group apart from agility and starting speed (5 m sprint). No difference was observed in motor co-ordination tests, using the Köperkoordinationstest für Kinder (KTK) (Kiphard and Schilling, 2007). When accounting for APHV fewer differences emerged from the groups: U16 – BMI, grip strength, lower body power, agility and speed (F = 9.66, P < 0.001, η^2 = 0.928), U17 – body mass, BMI and 30m speed (F = 5.03, P = 0.002, η^2 = 0.878). The authors cite the possibility of the interaction of training volume to explain fitness differences between groups, and propose that testing should include multiple factors that are affected and not-affected by maturation status to obtain a better picture of development. This is supported as age and maturation status assessed by pubic hair growth have been found to vary in contribution to elite football players skill levels between U13 and U15 age groups (Malina *et al.*, 2005). Age, maturation status, years of experience and body size were all significant contributors although minimally (8 – 21%) to four out of six football skill tests, which leaves other factors to explain the majority of expertise at this stage.

Lloyd and colleagues (2015c) studied the change in physical performance and functional movement skill scores in a sample of football players between 11 and 16 years old. The U16 group were superior in all physical tests (P < 0.05, effect sizes 1.25 – 3.40) in lower body power, reactive lower body strength index and agility, however no difference was observed between the U11 and U13 groups in physical performance although the U13 were more mature ($P < 0.05$). A number of fundamental movement skill tests were correlated with physical performance ($P < 0.05$), once maturity was accounted for only reactive lower body strength index remained significant between U13 and U16 ($P < 0.05$). It was concluded that maturity affected tests that require more physical prowess, and fundamental movement skill scores (in-line lunge in particular) affects dynamic skill tests involving unilateral stabilisation, although maturity will still impact scores if there is a strength and physiological component. The lack of difference between U11 and U13 in comparison to U13 to U16 reveals the non-linear trajectory of physical development of young athletes, which must be accounted for in TID to ensure accurate assessment of ability.

Previous research has shown that the intraseasonal and long term stability of anthropometrical and physical data is highly variable, especially through adolescence (Buchheit and Mendez-Villanueva, 2013; Francioni *et al.,* 2016). Further adding to the limitations of using purely physical characteristics for selection in young athletes, however physical measures have been shown to have good absolute reliability and high to very high relative reliability irrespectively of age and/or maturation status when two sets of tests were performed over a period of a month (Buchheit and Mendez-Villanueva, 2013). Due to the individual variation and the instability of physical characteristics through periods of varying growth, regular testing is advised to be able to cater for in-season fluctuations (Francioni *et al.,* 2016).

2.4 Talent Development

Considering the limitations and poor predictive qualities of TID in elite sport, there has been a move away from attempting to predict future performance to focusing on providing the best environment and opportunities to maximise potential (Abbott *et al.,* 2002; Abbott and Collins, 2004; Martindale *et al.,* 2005; Vaeyens *et al.,* 2008) commonly termed Talent Development (TDE). This corresponds with how TDE was described by Williams and Franks (1998) where athletes are provided with an environment to allow for suitable learning to achieve their potential. Vaeyens *et al.* (2008) advised elite talent programmes to more fully understand the skills and factors that are evident in successful elite senior athletes, and therefore apply resources towards enhancing younger athletes' ability to learn and work towards what it takes at the highest level. That athletes are profiled longitudinally and not just assessed on one-off snapshots of performance, so support may be given based on strength and weaknesses based on developmental needs, and importantly that maturation status is accounted for in athlete development alongside the natural variation in physical performance. Focus must be towards characteristics that indicate the potential to successfully progress into elite adult participation (Abbott and Collins, 2004). Burgess and Naughton (2010) concluded that programmes should be more inclusive and not use these factors as criteria for inclusion, but to more effectively support the athlete.

Talent Development is an unpredictable process containing potentially confounding variables such as maturation status/maturity timing, sociocultural, and political and economic factors. Programmes should be holistic, embrace multi-disciplinary factors and take individuality and the non-linear trajectory of development into account (Bergeron *et al.,* 2015; Gulbin *et al.,* 2013). Athletes are far too often put under competition and performance pressure at an early age (Burgess and Naughton, 2010) which increases the likelihood of early exit from talent programmes and burnout (Güllich and Emrich, 2012). Martindale *et al.* (2005) were in agreement and stated five generic features of effective TDE: to have long term targets and plans, involve a wide range of support, emphasise development not early success, track individual development and integrate the many factors of developing elites within a systematic process.

2.4.1 Models of Talent Development

There have been a number of authors who have attempted to characterise the aforementioned unpredictable process of talent development: Participation Model of Sport Development (Bailey and Collins, 2013), Developmental Model of Sport Participation (Côté *et al.,* 2009), Differentiated Model of Giftedness and Talent (Gagné, 2004), that incorporate key theories of development such as Deliberate Practice (Ericsson *et al.,* 1993) and Stages of Learning (Bloom, 1985). Within these models however are limitations of simplicity versus complexity, and the amount of empirical evidence to support them. The following section will assess two of these models: Differentiated Model of Giftedness and Talent (Gagné, 2004) and the Developmental Model of Sport Participation (Côté *et al.,* 2009) to provide the reader with their respective strengths, but also the limitations of the use of models within the TDE environment.

2.4.1.1 Differentiated Model of Giftedness and Talent (DMGT)

Due to disagreement with the use of terminology around defining talent and the development process, Gagné (2004) sought to clarify the terms of giftedness and talent. In this model natural abilities, or gifts, are translated into systematically developed skills, or talents via developmental processes that are affected both positively and negatively by a combination of intrapersonal and environmental catalysts and chance.

Giftedness was defined as the possession and use of untrained and spontaneously expressed natural abilities in at least one activity domain to a degree that places them in the top 10% of age peers, within the core domains of intellectual, creative, socio-affective and sensorimotor ability. Talent defined the outstanding mastery of systematically developed abilities, skills and/or knowledge in at least one field of human activity i.e. sport/music, to a degree that places them in the top 10% of age peers who are or who have been active in that field (Gagné, 2004). Gagné used the top 10% threshold within giftedness and talent as being outstanding from estimates of IQ, with higher thresholds included labelled as mildly to extremely constituting a further 10% of the previous level ending with extremely characterised as being better than 1:100,000 in the general population. A limitation of using such arbitrary thresholds through talent development is that it doesn't allow for natural variation in performance along the pathway to elite sport participation, as different acceleration in physical growth or another significant event could mean a child falls out of the top 10% and therefore is suddenly not labelled as being talented anymore. Gagné (2004) however stated in the education field that students who are talented maintained their talented status throughout development, though this is challenged in a sport setting as previous research has shown there is not a standard linear progression through elite participation in top level athletes (Gulbin *et al.,* 2013) and being labelled as talented at Youth level does not imply future elite success (Abbott *et al.*, 2002). Possibly a reason for the lack of uptake of this model in sport research is its educational formation and background and therefore perceived limited application to talent development pathways in sport (Lloyd *et al.,* 2015a).

Gagné's developmental processes observe an overlap with the theory of Deliberate Practice and development of expertise (Ericsson *et al.,* 1993) with the inclusion of significant amounts of time and effort in formal institutionalised and non-institutionalised learning as central to the translation of gifts to talents. Alongside these processes are informal learning, similar to deliberate play activities (Côté *et al.,* 2003) and physical maturation or growth of all physical and physiological processes. These processes are affected positively and negatively by catalysts located intrapersonally such as physical or psychological characteristics or environmental effects whether geographically in relation to resources or interactions with other key stakeholders e.g. family, coaches, and other athletes. Alongside chance from genetics, birthplace and socioeconomic status, this model embraces the multidimensional and complex structure of talent development, and includes space for nature and nurture in achievement of expertise.

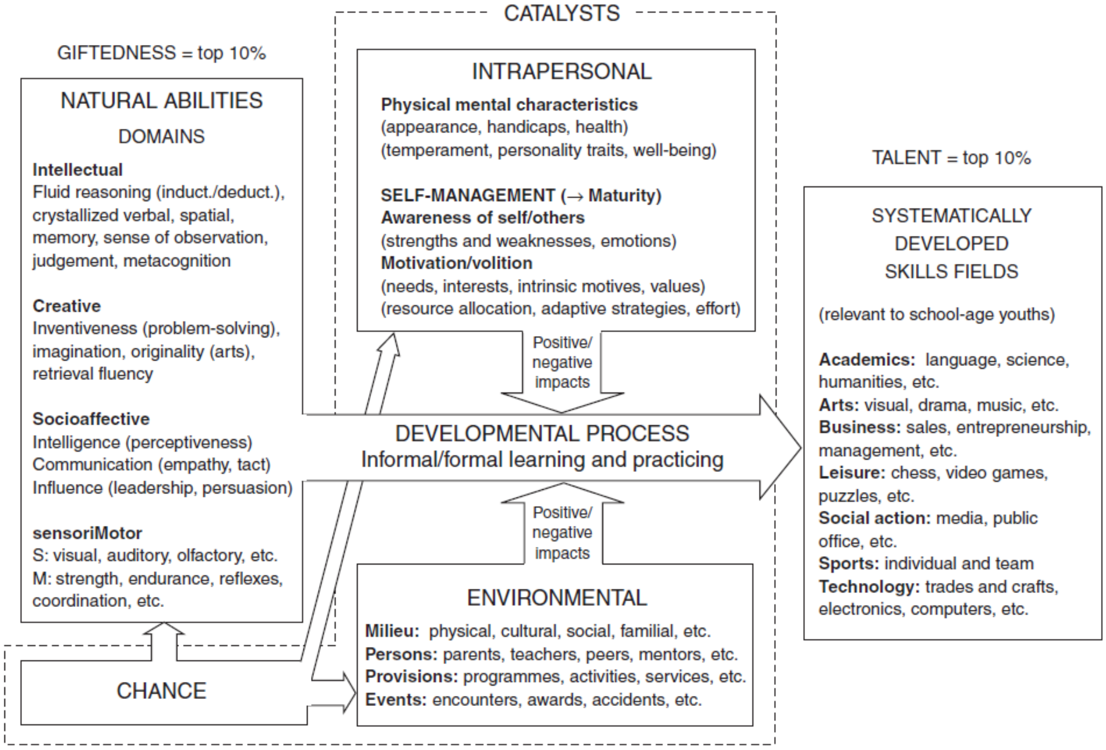

Figure 2.2 Differentiated model of giftedness and talent (Gagné, 2004)

2.4.1.2 Developmental Model of Sport Participation (DMSP)

Central to the DMSP are the two different types of environment that occur in early youth years that may lead to future elite performance: Sampling and specialisation. Sampling involves firstly participating in a number of sports allowing children to learn a variety of skills from a range of scenarios and environments with a mixture of physical and psycho-social demands (Côté *et al.,* 2009). Secondary to sampling includes engaging in deliberate play, an informal activity based on a structure that allows sport to be played emphasising enjoyment (Côté *et al.,* 2003). Specialisation is characterised by a high volume of deliberate practice, which is completed to improve performance and requires effort, but is not inherently enjoyable (Ericsson *et al.,* 1993). Côté and colleagues developed the four stages of the DMSP from the previous work of Bloom (1985) who formulated different phases of learning from interviews with elite Australian and Canadian athletes:

1. Sampling Years (6 to 13 years): The focus at this stage is fun with activity consisting of play and multi-sport participation. Fundamental movement skills are developing during this time which act as a foundation for future participation
2. Specialising Years (13 to 15 years): Greater importance is placed on fewer sports, deliberate play is still evident, but reduced with an increase in deliberate practice and sport-specific skill development.
3. Investment Years (15 to 18 years): Commitment to a single sport with large increases in the volume of deliberate practice and sport-specific strategy, skill and competitive experience.
4. Maintenance Years (18+ years): Time is spent perfecting and maintaining talent.

It is agreed that expert performance must include practice and play in a deliberate form or otherwise, this accumulation of time must include a significant volume of deliberate practice (Rees *et al.,* 2016; Suppiah *et al.,* 2015). What is debated is the amount of deliberate practice that must be completed to achieve success at the elite level. Ericsson and colleagues' (1993) seminal paper proposed that many characteristics that were initially thought to be predisposed by innate talent were actually the culmination of approximately ten years of structured training. This led to the widely regarded minimum 10,000 hour 'rule' for expert performance which Ericsson recently stated wasn't intended to be the outcome of their research as he accepted that there will be individual variation (Ericsson, 2013). In fact the duration of time and amount of hours to achieve expert performance have been shown to be significantly less with 7.5 years to achieve elite national participation from novice (Rees *et al.,* 2016) and as low as 14 months to progress from novice to Winter Olympian in Skeleton (Bullock *et al.,* 2009). Olympic field hockey players took as low as 4,400 hours of sport-specific practice to win Olympic gold, and 4,500 hours from novice to German national football team selection (Hornig *et al.,* 2014). Evidence of rapid success of Talent transfer projects may be partially explained from the understanding in team ball sports that practice hours accumulated in other sports may contribute/replace the hours conducted in the current sport (Baker *et al.,* 2003). The difficulty of using training hours to distinguish success in sport is that firstly, hours of training may not be classed with the same effect, as sport-specific training may include a number of different modes of training e.g. strength training or tactical training. Secondly this range of training stimulus may be performed with various amounts of fatigue/intent that would be extremely difficult to quantify (Tucker and Collins, 2012).

In support of the DMSP, the International Journal of Sport Psychology (ISSP) produced a position stand on Specialisation versus sampling (Côté *et al.*, 2009) which was later re-visited by Côté and colleagues who used the GRADE system to quantify the quality and confidence of its evidence base (Côté *et al.,* 2014). The review highlighted that the development environment will need to vary based on different athletes at different ages, that prolonged participation and later success is based around early sport diversification and deliberate play initially followed by a greater volume of deliberate practice and eventually specialisation. The differences between sports in terms of the need for early specialisation was acknowledged, however this framework will ultimately be more costly as will involve more athletes for a longer period of time, without necessarily a greater chance of success (Côté *et al.*, 2014).

A strength of the DMSP is the inclusion of choice within development. Alongside each of the four stages presented above are what were termed the Recreation Years, where a participant may choose to drop out and continue to progress with sporting involvement for leisure benefits. This provides participants with a route to move back towards talent-focused involvement at a later date, allowing for a more individual progression to elite sport. A major discussion point on the simplicity of the model exists as the DMSP is based around achieving elite status from 18 years of age, which may not be representative of the age at which athletes reach the elite level across all sports and especially when considering the termed Early specialisation sports such as artistic/rhythmic gymnastics, figure skating and platform diving, where expert performance is typically observed before full maturity (Rees *et al.,* 2016). Challenge to this model also comes from the lack of consideration of physical development and maturation status and the lack of training prescription (Lloyd *et al.,* 2015a). As the model is more focused on psychological and skill expertise development i.e. a runner may have developed exceptional technique, but does not have the physiological development to match and therefore may not achieve their potential. The following section will consider the physical aspect of talent development.

2.4.2 Talent Development and Physical characteristics

Numerous studies have demonstrated that proficiency in sport-specific skills are able to differentiate between elite and non-elite athletes throughout the TDE process (Elferink-Gemser *et al.,* 2004; Falk *et al.,* 2004; Vaeyens *et al.,* 2006). Many of these skills are complex, and are underpinned by the development of fundamental skills progressing from an early age (Abbott *et al.,* 2002; Gagné, 2004). In sport, athletes with potential are understood to display a wide range of these fundamental skills such as running, hopping, jumping and throwing, increasing the probability of successful progression to participation in higher skill levels of performance (Jess and Collins, 2003). Absence of these foundation skills may affect an athlete's ability to develop the physical requirements to allow them to compete in future elite sport (Faigenbaum *et al.,* 2013).

Early specialisation does not favour the development of fundamental skills in elite athletes, sampling different sports in late childhood and early adolescence acts as a foundation of mental and physical skills (Ericsson, 1998). Proposing an advantage, and perhaps necessity, to develop a sound grounding in fundamental skills in order to become successful in sport (Abbott et al., 2002). Young athletes who had not specialised at an early age scored higher in tests of motor co-ordination (Fransen *et al.,* 2012). This provides support for fundamental movement skills as a critical inclusion at younger stages, progressing into more complex sport specific skills and more generalised physical characteristics such as balance, co-ordination, strength, speed, agility and power (Bergeron *et al.,* 2015). This skill transition creates the foundations, athletic motor skill competencies (AMSC) (Moody *et al.,* 2013) (Figure 2.3) or building blocks (Abbott *et al.,* 2002) to future long-term athletic development, and increases the chances of acquiring physical capacities and skills that may transfer to other sports or disciplines (Gulbin, 2008) and enable athletes to overcome a range of challenging athletic situations and to perform proficiently with confidence and optimal technique (Bergeron *et al.,* 2015).

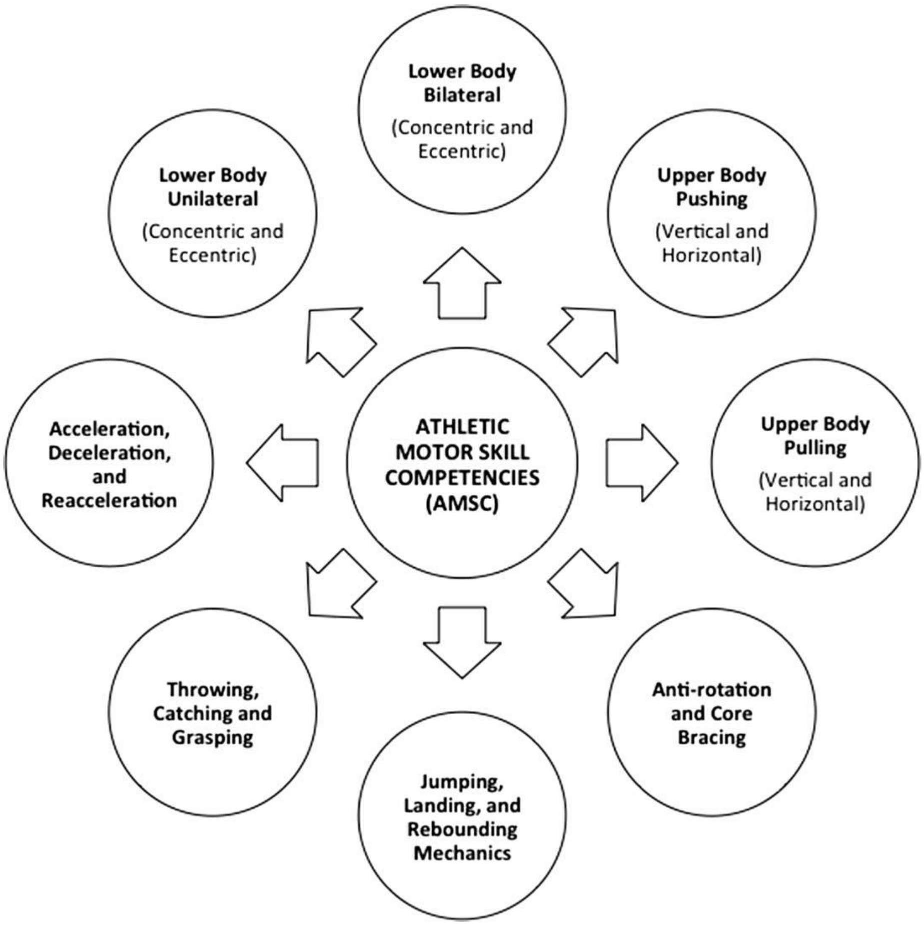

Figure 2.3 Athletic Motor Skill Competencies (AMSC) (Moody *et al*., 2013)

It has been previously documented that to achieve elite performance across a range of sports training must include a large amount of deliberate practice volume (Rees *et al.,* 2016; Suppiah *et al.,* 2015) and that the exact amount is difficult to quantify as training may be performed with varying environmental constraints (Tucker and Collins, 2012). One of these constraints is the amount of fatigue experienced, as physical fatigue has been shown to affect skill levels in game-based simulation (Russell *et al.,* 2011). This adds weight to the concept that it is not just about the volume of deliberate practice, but the intensity and quality of the training, including making sure that the athlete has the necessary physical requirements (Kliegl *et al.,* 1989). Elferink-Gemser *et al.* (2010) conclude that successful elite athletes have the capability to develop faster from the same amount of hours, partially through an enhanced physical capacity.

Sampling different sports and activities should be supported with maturity-based physical training interventions (Faigenbaum *et al.,* 2013; Lloyd *et al.,* 2015a) as multi-sport participation alone has been shown to be inadequate to complete the recommended exercise guidelines of 60 mins per day of moderate to vigorous physical activity (Leek *et al.*, 2011). Early engagement with physical training, in particular individually constructed

Strength and Conditioning (S&C) training created to address areas of physical deficiency has been advised by the International Olympic Committee in a Youth-specific edition (Mountoy *et al.*, 2008). It is important to acknowledge that children have specific training needs that makes them different from adults and should not be treated as such (Faigenbaum *et al.,* 2013). McGuigan *et al.* (2012) reviewed the impact of strength training in sporting performance, and found it to be an integral part of athletic preparation. The transfer into sporting activity across different sports varies, and needs to be better understood. Similar to International Olympic Committee guidelines, for maximum impact training should be individualised and varied specific to the goals of the athlete (McGuigan *et al.,* 2012).

Early development of a broad range of physical characteristics can improve performance and reduce the risk of injury (Myer *et al.,* 2013). Although sport may account for up to 30% of injuries in youth (Emery, 2013), engaging in strength training can have a positive effect on injury prevention in both acute and overuse injury (reduction of approximately a third and a half respectively), interestingly stretching had no effect on injury prevention (Lauersen *et al.,* 2014. Previous research indicates that child and adolescent athletes without the exposure of systematic S&C and injury prevention training will require additional support to correct movement disfunctions/imbalances or during rehabilitation from injury (Emery *et al.,* 2007; Emery *et al.,* 2010). Once specialisation occurs in a sport, the volume of repetitive movements increases which predisposes the athlete to a greater chance of injury. Therefore it is crucial that athletes are conditioned to perform a variety of movements with competency in a range of environments to develop physical robustness with the necessary ability to produce and attenuate force to prepare for the demands of high volume sport-specific training and competition (Lloyd *et al.,* 2015b). It is important to limit injury risk that this transition is not rushed to allow progressive adaptation to the new demands (DiFiriori *et al.,* 2014)

In addition to the benefits of injury prevention, skill development and performance, the development of fundamental movement skills and general physical characteristics can enhance self-esteem, leading to more social interaction, sporting and physical activity participation and wellbeing in general (Lloyd *et al.,* 2012). Physical training has also been linked to decrease risk of health conditions such as obesity and cardiovascular disease (Faigenbaum *et al.,* 2013).

2.4.3 Models of Talent Development (Physical)

Put succinctly the International Olympic Committee released a consensus statement on youth athletic development: "The goal is clear: Develop healthy, capable and resilient young athletes, while attaining widespread, inclusive, sustainable and enjoyable participation and success for all levels of individual athletic achievement" (Bergeron *et al.*, 2015, p.1). The following section will explain the progression in models created to characterise physical aspect of TDE, moving along continua of focused to holistic, and observation to empirical research foundations.

2.4.3.1 Long-Term Athlete Development (LTAD) model

The main aims of the LTAD model are to increase the number of athletes who can be successful at the elite adult level, and provide a platform for coaches and athletes to realise their potential and maintain their participation in sport (Stafford, 2005). The model comprises of five main stages (Figure 2.4) beginning with developing the FUNdamentals involving multi-sport and activity participation with the aim of enhancing fundamental movement skills and techniques, learning to train, training to train, training to compete and training to win. Additional to these stages is retirement and retainment where athletes are hopefully retained in the sport past competitive involvement, possibly in coaching or officiating (Bayli and Hamilton, 2004).

Central to the LTAD concept is the long-term commitment to training in line with the previous work of Ericsson *et al.* (1993), and de-emphasising the importance of competitive results during childhood and adolescence, avoiding what has been termed a 'peaking by Friday' approach where short-term performances are prioritised over long term development (Bayli and Hamilton, 2004). The LTAD model seeks to address the balance of an individual's training and competition load based on maturation status rather than chronological age (Ford *et al.,* 2011). The model prescribes an increase in the percentage of competition and competition-specific training as athletes development through the stages, with a ratio of 70:30 in favour of training at the Learn to Train stage to 75:25 in favour of competition-specific training/competing at the Train to Win stage (Bayli and Hamilton, 2004). Bayli (2013) states that these percentages may change between sports and vary between individual's specific needs.

The most controversial aspect of the LTAD surrounds the windows of opportunity that are designated around key steps in maturation, such as around the timing of peak height velocity (PHV), where it is possible to accelerate physical development (Viru *et al.,* 1999), and the notion that if these windows are missed that the athlete will not realise their full athletic potential and have been termed as 'make or break' for the athlete (Bayli and Hamilton, 2004). Recent reviews of the LTAD have cited a lack of empirical evidence behind these windows of opportunity (Bailey *et al.*, 2010; Ford *et al.,* 2011; Lloyd *et al.,* 2015a), in fact Bayli and Hamilton (2004) themselves claim the model to be based on empirical *observations*, and therefore the model's structure is flawed. Ford *et al.* (2011) acknowledge the barriers of a lack of well-controlled longitudinal data in youth research though state that there is no evidence to the lack of exploitation of these windows resulting in any ceiling effect. In fact limiting aerobic training to certain stages is inappropriate and the trainability of these factors and the stimulus-response relationship, especially within these windows in unclear. Bailey *et al.* (2010) contend that optimising training through these windows may accelerate athletes towards their ceiling, but absence of this would not limit the physical potential of the athlete.

Even though the 10,000 hour rule and windows of opportunity concepts have been challenged and with a lack of an empirical research base, the LTAD has enhanced sports' awareness and understanding of maturation and development (Lloyd *et al.,* 2015) and has been among the most influential models adopted by national sporting programmes to inform policy (Bailey *et al.,* 2010). The model acknowledges early and late-specialisation sports and mentions mental-cognitive/emotional development, but is constrained by physiological measures and biological processes and is predominantly based on physical development and therefore would be more suitable for talent development if it embraced more of a holistic approach (Ford *et al.,* 2011).

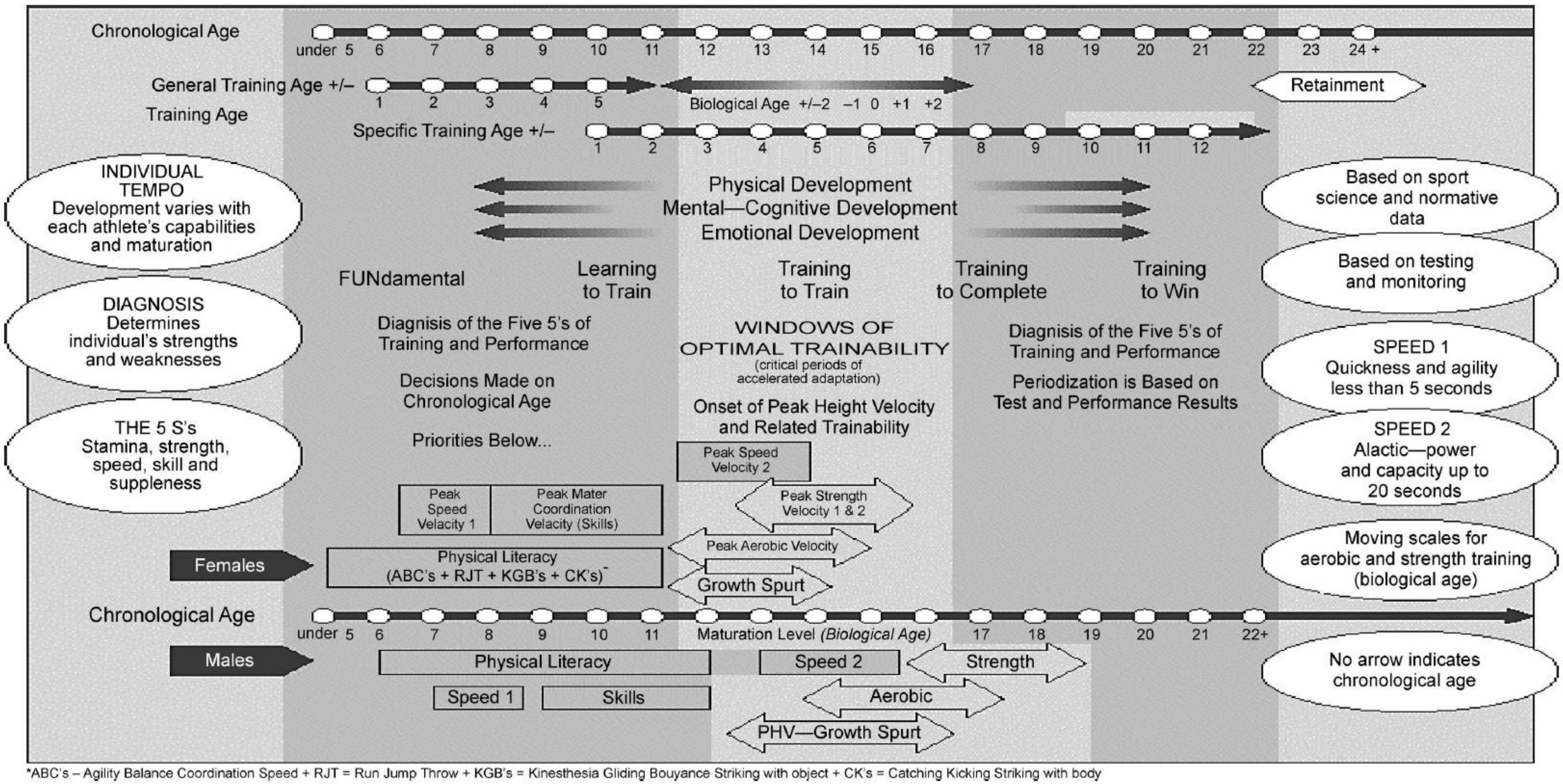

Figure 2.4 Long-term athlete development (LTAD) model (Bayli and Hamilton, 2004)

2.4.3.2 Youth Physical Development (YPD) model

The YPD model is considered a strategy for the physical development across childhood and adolescence (Lloyd *et al.,* 2015a), but improves upon the LTAD model from being constructed from an empirical evidence base (Lloyd and Oliver, 2012). The YPD model is not just aimed at the pursuit of the pinnacles of sport and athleticism, but also the development and maintenance of well-being and participation. Lloyd and Oliver (2012) assert that the majority, if not all, components of fitness are trainable at all times during development although there are times where certain components may be prioritised. The mechanisms and magnitude of adaptation will differ based on maturation status and the timing will vary due to individual variation (Lloyd and Oliver, 2012). The model displays the average maturity trajectory of boys and girls, however there is a great need to acknowledge individualisation of exercise prescription for all youths (Lloyd *et al.,* 2015a).

Similar to the LTAD model the YPD model includes: fundamental movement skills, sport specific skills, speed, strength and endurance, and adds: agility, power, hypertrophy and metabolic conditioning as fitness components of athletic development. The key fitness components of the YPD model are strength and movement competency - Lloyd and Oliver (2012) state that: “strength should be a priority at all stages of development for both males and females” (p.64). Although all relationships have not been validated in youth populations, greater strength and movement competency have been shown to decrease injury rates, increase performance, increase health factors and well-being plus increase sporting participation (Lloyd and Oliver, 2012).

The YPD model provides evidence the challenge to the windows of opportunity concept which is central to LTAD model. To use strength as an example, previously the LTAD model considered the window of opportunity to be 12 – 18 months post-PHV in boys and immediately post-PHV or at onset of menarche in girls (Bayli and Hamilton, 2004) partially from increases in circulating androgens and development of the structure of musculotendon units (Myer *et al.,* 2011). Lloyd and Oliver (2012) agree with the benefits of training strength where there are improvements in testosterone-induced muscle mass and mechanical/co-ordination factors, however due to the levels of neural plasticity during pre-adolescence (Borms, 1986) there is strong rationale to train for improvements in strength (and other factors) outside of the previously acknowledged stages of development. Developing strength in childhood is not counter-productive to development and holds minimal risks when safe and effective programme design and implementation is delivered by appropriately qualified personnel (Lloyd and Oliver, 2012).

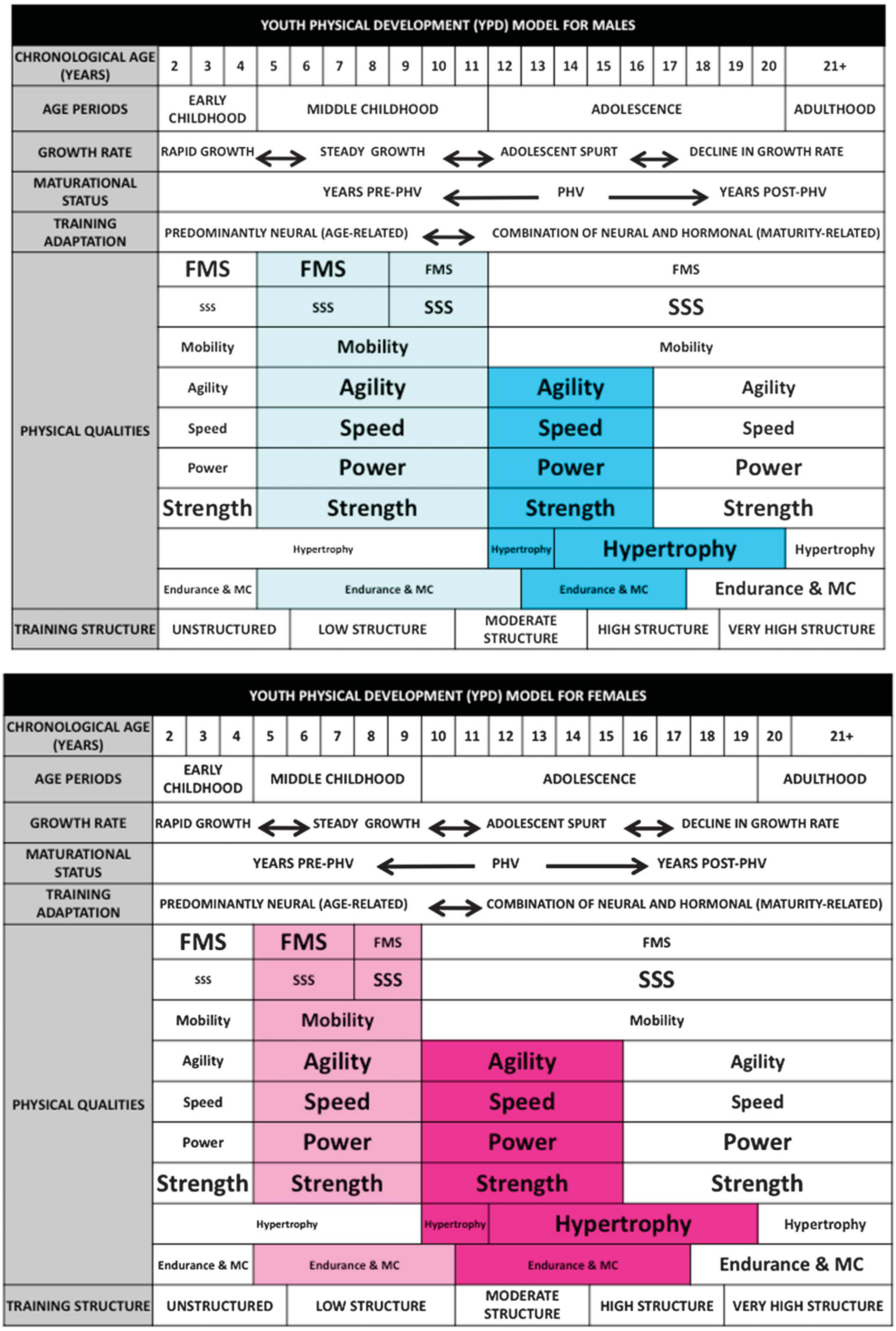

Figure 2.5 Youth Physical development (YPD) model in males (blue) and females (pink) (Lloyd and Oliver, 2012). Note: FMS – fundamental movement skills, SSS – sport specific skills, MC – metabolic conditioning.

Although not displayed on the model diagram, the authors highlight the importance of training age – defined by the numbers of years participating in formalised training.

Therefore practitioners must be aware of the individual's chronological and biological age, in addition to their training age to design a safe and effective programme (Lloyd and Oliver, 2012). The studies within Chapter 6 to Chapter 8 assess maturation in further depth, including the impact it has on TDE.

The addition of an empirical evidence base for the YPD model makes it a more valid framework for youth athletic development and to provide a structure of physical training (Lloyd *et al.,* 2015a), however it is limited as a model for talent development in the same way as the LTAD model in that the basis is purely physical.

2.4.3.3 Composite Youth Development (CYD) model

To progress the YPD model, Lloyd and colleagues (2015a) merged the areas of youth athletic development and TDE and put forward a holistic model of youth development. The CYD model uses the framework of the YPD model (Lloyd and Oliver, 2012) and integrates it with an adapted version of the DMSP (Côté *et al.,* 2007) and the mental training guidelines of Visek and colleagues (2013) to provide the talent and psycho-social elements of development.

The CYD model includes the same nomenclature as the DMSP including the investment years, sampling years and specialising years, but the authors have adapted the characteristics of these stages. Early childhood is termed as the investment years as children invest time in learning and exploring a broad range of fundamental movement skills and activities/sports with a focus on fun-based learning and encouraging social interaction. When moving from middle childhood to early adolescence participants begin sampling a variety of sports and activities while training all fitness characteristics, but focusing on fundamental movement skills and strength. At this point in youth development there is an increase in the weight placed on enhancing feelings of self-worth and self-esteem as pier comparison becomes more commonplace (Visek *et al.,* 2013). Individuals should to be empowered with their own development, to take responsibility for their own progress at this stage and when transitioning into the specialising years, where individuals choose to specialise in a sport for competition or recreation. The two reasons to participate may display a transitional nature where external or internal factors result in drop-out which may only be temporary. Training in this stage is highly structured and tailored to the individual and sport, with key areas being strength and sport specific skills.

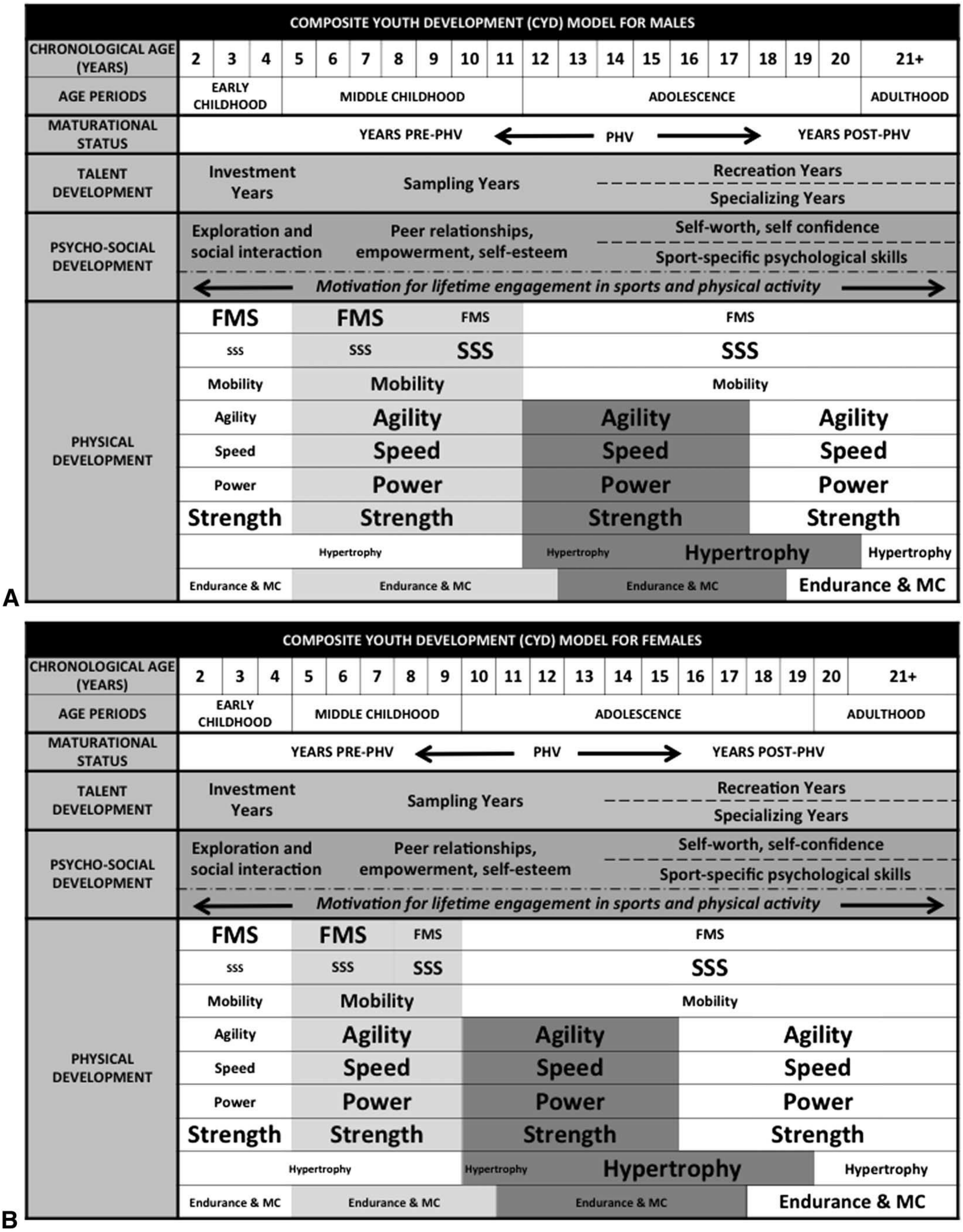

Figure 2.6 Composite Youth development model (CYD) for males (A) and females (B) (Lloyd *et al.*, 2015a)

It is important to note that any model of TDE should not be viewed as a blueprint to success, and shouldn't be used as fixed directives within a talent programme. Generic guidelines taken from models should be individually tailored to fit the unique trajectory that an athlete is on, making sure that practice, delivery and support are age and stage appropriate (Lloyd *et al.,* 2015a). For example an athlete with a low training age/experience should not engage in high volume sport specific skill work before developing a sound foundation of fundamental movement skills (Faigenbaum *et al.,* 2013). Further research is required to be completed and implemented in talent programmes so that guidelines can be given from a strong empirical background where possible (Lloyd *et al.,* 2015a).

2.4.4 Benchmarking development

A key aspect of a TDE programme is having a clear pathway of progression to elite senior sporting success. Using the process of benchmarking young athletes' progression against the development of the most successful senior athletes relative to their maturation status, TDE programmes would be able to identify and monitor athletes who are on a trajectory to elite success and therefore provide support and resources to maximise potential (Allen *et al.,* 2014; Vaeyens *et al.,* 2008). There have been examples of different sports producing performance trajectories in predominantly closed skill sports of swimming (Allen *et al.,* 2014), cycling (Schumacher *et al.,* 2006) and skeleton (Bullock and Hopkins, 2009). Allen *et al.* (2014) used individual quadratic trajectories of swimmers at the Olympic level swimming the fastest times between 2008 and 2012 Olympics. The authors found large variability of performance between individuals and that the model was not sensitive enough below 16 years old in boys and under 14 years old in girls, this could be due to the instability of the impact of maturation during adolescence (Buchheit and Mendez-Villanueva, 2013; Francioni *et al.,* 2016) or from the multiple factors that interact towards performance during youth athletes transition to adult age (Vaeyens *et al.,* 2008). A mean value for performance was plotted against chronological age with 90% reference values in all events (Figure 2.7) with different trajectories identified between events and gender (Allen *et al.,* 2014). Maturation status was not accounted for in performance trajectories which is a limitation of this study, suggesting the need to track physical and anthropometrical characteristics alongside performance to gain a full picture of TDE.

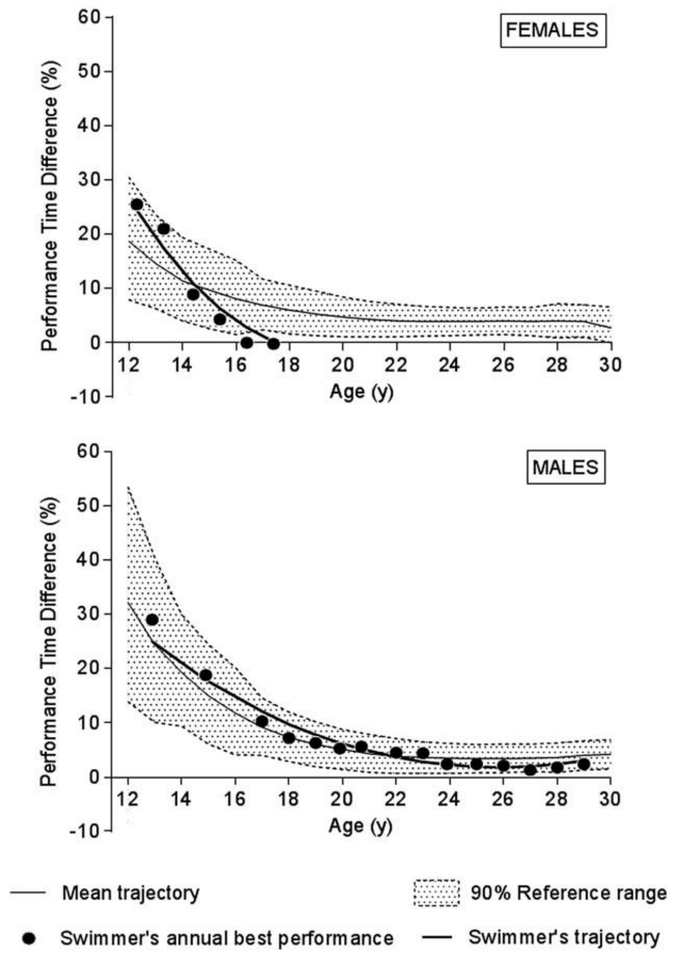

Figure 2.7 Mean performance time difference (%) and 90% reference range between age-related predicted performance time and 2012 Olympic gold medal time for female and male middle-distance (200 m) swimmers (Allen *et al.,* 2014). Male and female Olympic swimmer trajectories are displayed

Vaeyens *et al.* (2008) stated that a minimum competence in components of performance should be required to achieve success at the elite level. Perhaps the TDE programme should identify what the key characteristics are of successful development and benchmark these against successful elite athletes, it is important to note that performance outcomes may change over time so this would need to be updated regularly to remain accurate (Lawton *et al.,* 2012). For this to be a more robust process, TDE programmes must take into account the individual non-linear pathway of physical development through maturity, but also variation imposed from non-physiological factors such as skill acquisition and psychology (Malina, 2004). If physical testing is used in this process, the use of simple tasks without a high skill (or sport-specific skill) component should be employed so that an extra advantage is not gained from greater years of training within a sport or just purely from an increased length of time in a TDE programme (Lidor *et al.,* 2009). Physical factors should not be viewed as predictors of success, but to help support the athletes' individual development curve, where focusing on annual development rate could be an important factor in potential (Lawton *et al.,* 2012). Talent Development programmes must be aware that athletes will typically progress at different rates that could still ultimately end in success, and that strengths in some areas may compensate for weaknesses in others (Williams and Ericsson, 2005). It is for these reasons that tracking athletes longitudinally in an inclusive TDE programme is essential (Elferink-Gemser *et al.*, 2010), and the information not to be used for deselection (Burgess and Naughton, 2010). The sports that have generally employed trajectories towards elite senior success have been closed sports, therefore if this process is attempted in more open sports such as team sports or sailing the relative contribution of factors must be viewed in context of the number of factors that affect performance and development (Reilly *et al.,* 2000).

To be effective in assessing and monitoring the physical characteristics of developing sailors, it must be clear what the requirements are of competing at the senior Olympic level and what the current understanding is of physical characteristics at pathway level. The following section evaluates the current research base of physical requirements in sailing.

2.5 Physical requirements of sailing

2.5.1 Olympic sailing

The majority of studies determining the physical requirements of Olympic sailing were published over 15 years ago. The overwhelming majority of research has focused on hiking sailors, in particular the Laser class. In light of this and the recent evolution of Olympic sailing highlighted in Figure 1.6, there is a need for advancing research into the physical profiles of Olympic sailors of all classes, especially in light of the fact that only six out of 15 sailing positions at the Rio 2016 Olympic Games involved hiking. Bojsen-Möller *et al.* (2014) review grouped sailors into distinct categories relating to the movements performed termed Hikers, Side-Hikers, Trapeeze and Board sailors. With the removal of 'Side-hiking' from the 2016 Olympics, this can now be simplified into: Hike, Trapeeze and Board sailors.

Table 2.3 Categories of sailing positions in the Olympic pathway

Category	Level	Class/Position
Hike	Youth	Optimist, Topper, RS Feva helm/crew, Cadet helm/crew, Mirror helm/crew, Laser 4.7, Laser Radial, Laser, 420 helm, 29er helm
	Olympic	Laser Radial, Laser, Finn, 470 helm
Trapeeze	Youth	420 crew, 29er crew, Spitfire helm/crew
	Olympic	49er helm/crew, 49er FX helm/crew, 470 crew, Nacra-17 helm/crew
Board	Youth	Bic Techno 293, RS:X 8.5m
	Olympic	RS:X 8.5m, RS:X 9.5m

The following sections will review the sailing literature within the main areas of physical requirements of strength, strength-endurance, aerobic fitness and other physical characteristics within the different groups (in order of: Hikers, Trapeeze sailors and Boardsailors) within elite Senior, Junior and Youth sailing.

2.5.1.1 Hikers

As briefly mentioned in the thesis introduction and supported by Bojsen-Möller *et al.* (2014) review on physical requirements of Olympic sailing, the majority of research has focused on hikers and hiking performance. Even though the number of sailing positions that involve hiking has decreased in the Olympic Games, hiking still features in five of the ten events when including male and female classes therefore the research still potentially has a great impact on the success of a country's involvement in sailing at the Games overall.

Understanding of the physical requirements of hiking has evolved over the past 40 years, early work focused on hiking being an isometric activity affecting the knee extensors and anterior trunk muscles (Niinimaa *et al.,* 1977; Plyley *et al.,* 1985). More recent research has classified the movement as "quasi-isometric" (Spurway, 2007, p.1081) due to upper body movements of sheeting and trimming the sails, combined with the shifting of load between legs and other muscle groups to cope with the discomfort of ischaemia from reduced blood flow (Blackburn, 1994; Vogiatzis *et al.,* 2011) and overcoming the varying forces created by environmental conditions of wind gusts and waves. The exact demands of hiking however are debated (Castagna and Brisswalter, 2007; Cunningham and Hale, 2007). With on-water measurements of the physical demands being difficult, a number of on-land hiking benches and simulators using the hull of the boat have been designed to mimic the demands

(Aagaard *et al.,* 1998; Blackburn, 1994; Callewaert *et al.,* 2013b; Cunningham and Hale, 2007; Larsson *et al.,* 1996; Maisetti *et al.,* 2006; Vangelakoudi *et al.,* 2007).

2.5.1.2 Maximal Strength

It is known that competitive sailing produces significant mental and physical demands, under light conditions complex psychological factors and experience are indicated to be characteristics of success (Niinimaa *et al.,* 1977). However as wind speed increases these mental demands are challenged by the physical requirements of counterbalancing the force from the sail and maintaining tension in the ropes (Plyley *et al.,* 1985). It is in higher wind conditions where maximal strength becomes more important as hikers will face larger forces across a number of muscle groups including the legs, trunk and upper body pulling muscles (Mackie *et al.,* 1999).

Hiking predominantly loads the knee extensors (quadriceps) with values of between 70 and 109% MVC in maximal isometric hiking positions at 150 to 180° hip extension (Sekulic *et al.,* 2006). Hikers in particular require high levels of isometric quadriceps strength, and this has been associated with hiking performance (Blackburn, 1994; Niinimaa *et al.,* 1977). Niinimaa *et al.* (1977) was one of the earliest studies to highlight the high maximal quadriceps force of elite sailors using a sample of Canadian national team members. Isometric force measured seated at 135° knee extension using a Clarke cable tensiometer in sailors was 106.4 ± 24.7 kg compared with 75.5 kg in oarsmen and 73.4 kg in swimmers. Vangelakoudi *et al.* (2007) supported this finding as when comparing 16 national and club-level Greek Laser sailors, national ranked sailors produced greater isometric knee extension torque at 145° of knee extension (166 ± 25 vs. 141 ± 30 Nm) than the club-level sailors. The particular knee angle was chosen as it most replicated the hiking position on the boat (Mackie *et al.,* 1999). Blackburn (1994) investigated 10 of the top 30 Laser sailors in Australia, and found higher isometric quadriceps torque to the sailors in Vangelakoudi *et al.* (2007) study of 270 ± 42 Nm (range 221 to 304), this difference may be due to limb set-up as sailors were positioned at 104° and 129° at the hip and knee respectively, this was calculated from how sailors performed hiking in races filmed prior to the study. Maximal isometric torque in this study was found to be moderately correlated to hiking performance ($r = 0.66$, $P < 0.05$). A recent study by Bourgois *et al.* (2015) analysed the components of the physical profile required for Laser sailors using an upwind sailing *emulation* developed by Callewaert *et al.* (2013a) based on previous literature and on-water data from hiking. Investigators measured a number of variables during hiking including assessing neuromuscular fatigue via surface electromyography (sEMG), measuring mean power frequency (MPF) and root mean square of the sEMG signal (RMS) that indicate motor unit firing frequency and fibre recruitment respectively. Sailors were ranked by their coaches for ability, and this was predicted through stepwise regression by 46.5% through exhibiting lower magnitude of MPF decrease. This lower decrease shown in neuromuscular fatigue was mainly predicted by maximal isometric quadriceps strength (57.8%) performed at 120° at the hip and knee (280 ± 49 Nm), highlighting the importance of maximal isometric strength to limiting fatigue in hiking.

Aagaard *et al.* (1998) measured maximal isometric and isokinetic quadriceps strength and its relationship with hiking performance in an elite sample of male and female sailors training for the Barcelona 1992 Olympics compared to a well-trained control group. These researchers found modest differences in maximal isometric strength between sailors and controls (323 vs. 308 Nm), though differences were more pronounced in maximal eccentric strength at low and moderate velocities (347 ± 70 vs. 294 ± 80 Nm at $30°\cdot sec^{-1}$; 350 ± 70 vs. 291 ± 68 Nm at $120°\cdot sec^{-1}$; 341 ± 81 vs. 284 ± 49 at $180°\cdot sec^{-1}$). It was interesting to note that the group of female sailors did not differ significantly to the control group in maximal eccentric quadriceps torque ($P > 0.05$), revealing that female sailors display a particularly high level of strength. It is clear from previous research that maximal isometric strength is related to hiking performance, though due to the quasi-isometric nature of hiking, it seems logical that a high degree of eccentric force is required to control the ever-changing forces of the boat which are corrected using small-amplitude dynamic movements (Aagaard *et al.,* 1998). The exceptionally high values of maximal eccentric quadriceps strength in male and female sailors in this study are proposed by the authors to be from a sailing-specific adaptation although they do not discount the possible interaction of strength training. Bojsen-Möller *et al.* (2007) report that due to the training history of elite sailors in their study that it is likely that the high values of peak quadriceps moment, calculated relative to body mass (eccentric/isometric/concentric: male: 3.66 ± 0.68/ 3.97 ± 0.66/ 1.82 ± 0.34), female: 3.84 ± 0.71/ 3.81 ± 0.58/ 1.60 ± 0.28 $Nm\cdot kg^{-1}$) were from the high physical demand of sailing volume. Sailors in this study were members of the Danish Olympic Sailing Team and when the group was reduced to purely hikers, levels of strength measured were comparable to elite athletes in explosive sports (e.g. volleyball).

Conversely in Bojsen-Möller *et al.* (2007) maximal knee flexion (hamstring) strength was lower, exhibiting a potential hamstring to quadriceps (H/Q ratio) deficit for hikers. This has potential implications for injury prevention around stabilising the knee joint, although Aagaard *et al.* (1998) found greater eccentric hamstring torque in elite sailors compared to controls, and therefore a greater capacity for stability around the knee joint from antagonist co-contraction, although the sample contained non-hikers which may explain the difference. Few studies have measured maximal isometric hamstring strength, Aagaard *et al.* (1998) found no difference in sailors compared to controls (130 vs. 131 Nm), possibly highlighting the importance of dynamic over static strength to support knee stabilisation during hiking.

The importance of trunk strength for sailing was highlighted by Niinimaa *et al.* (1977) remarking that sailing can be hard physical work and uses vigorous sustained contraction of the thigh and abdominals especially in hiking, however since then very few studies have investigated properties of trunk strength and even less measuring maximal trunk strength in elite sailors. Sekulic *et al.* (2006) measured the muscular activity of various muscles in elite hikers, including the trunk, during isometric holds at three fixed hiking positions, from seated inside the boat (90 to 120° hip extension) to full (150 to 180° hip extension). After the quadriceps, the abdominals were the second most loaded muscle (up to 60% MVC) at the full hiking position. Aagaard *et al.* (1998) recorded the most in-depth analysis of maximal trunk strength in elite sailors. Using a Kin-Com dynamometer measured maximal isometric and concentric torque (15 and $50°.s^{-1}$) of the trunk flexors and extensors. Elite sailors were stronger than controls in maximal trunk extension (386 ± 51 vs. 330 ± 61 Nm at $0°.sec^{-1}$; 352 ± 62 vs. 288 ± 54 Nm at $15°\cdot sec^{-1}$; 318 ± 65 vs. 266 ± 46 Nm at $50°\cdot sec^{-1}$). Maximal trunk extension values were similar between elite female sailors and male controls ($P > 0.05$) again displaying the high strength of female sailors. Maximal trunk flexion was not found to be different between groups. The higher values observed in trunk extension within the elite sailors was thought to be due to stabilisation of the low back and spine during hiking. Few correlations were found between maximal trunk strength and static and dynamic hiking performance on a hiking bench, with peak concentric trunk extension being moderately correlated in male hikers ($r = 0.64$ to 0.67, $P < 0.05$).

Few studies have investigated maximal upper body strength in elite hikers, even considering that the loading on the mainsheet in Laser sailing upwind in 15-20 knots of wind can average at 35% MVC with peak values of 90% MVC (Mackie and Legg, 1999). Early studies focused on maximal grip strength using a Stoelting dynamometer. Niinimaa *et al.* (1977) recorded values of 62.2 ± 5.4 kg, which was commented as being higher than most classes of sportsmen. Plyley *et al.* (1985) found similar values (558 ± 82 N, approximately 56.9 kg) which were higher than badminton players and swimmers (55.5 and 46.6 kg respectively), but lower than rowers (66.1 kg). Niinimaa *et al.* (1977) also measured maximal forearm flexion and extension (46.1 ± 4.5 and 38.1 ± 5.1 kg respectively), and found these to be lower than swimmers and rowers, however greater values (49.9 and 47.2 kg) were witnessed when the five best team members for overall sailing ability were separated from the mean (classified by team captain's rating).

2.5.1.3 Strength-endurance

Castagna and Brisswalter (2007) state simply: "apart from tactical or strategic aspects, performance in dinghy sailing relates directly to the capacity to overcome the external forces imposed on the boat" (p.95). The key word in this quote is capacity, sailing regattas at all levels of competition consist of multiple days of racing, with up to four races per day. Racing at elite level generally consists of 30 – 45 min races. A high degree of strength is required in hikers, especially when wind strength increases (Mackie and Legg, 1999) though once past a critical threshold strength to cope with the sailing forces (unknown at this time) it is more important to sustain performance over time to be successful. To put this physical demand into context Mackie *et al.* (1999) measured average forces produced in the lower and upper body in hiking classes to be 73 – 87% and 25 – 35% MVC respectively with peak force exceeding 100% in lower body and reaching 50% in upper body. At a potential of over two hours per day for five days in a row, this becomes a significant amount. What isn't accounted for in sailing research is that in most regattas, sailors are required to sail to and from the race course which can take over an hour each way depending on location. While this isn't sailed at maximum intensity, on days with high winds this adds a significant strain to the overall physical demand.

There have been a few studies using non-hiking strength-endurance tasks that have focused on the knee extensors and trunk when comparing between sailors and other sports people (Niinimaa *et al.,* 1977; Plyley *et al.,* 1985), level of sailing ability (Vangelakoudi *et al.,* 2007) and sailors and non-sailing controls (Larsson *et al.,* 1996). When investigating lower body endurance, Vangelakoudi *et al.* (2007) found elite Laser sailors sustained an isometric knee extension for ~40% longer than club level sailors of the same class (elite 160 ± 50 sec, club 101 ± 29 sec). Both groups worked at a similar target % of MVC (elite 42 ± 4%, club 46 ± 9%). Plyley *et al.* (1985) measured the drop off in force over 50 repetitions of knee extension at 50% MVC in members of the Canadian National Sailing Team, and the fatigue witnessed was lower than found in elite badminton players. Niinimaa *et al.* (1977) found no difference in endurance times at 50% or 75% MVC in elite sailors compared to 'normal' participants, however when analysing the top five team members according to a captain's ranking against the average, endurance time at 50% was much greater (137.2 vs. 83.7 sec) signifying the importance of endurance at this level of intensity in elite sailors. Non-specific trunk endurance reported in earlier research used the number of sit-ups completed in 60 s, and when compared to the general Canadian population (20-30 year olds) of 25 to 30 repetitions, sailors have consistently outperformed this: Niinimaa *et al.* (1977) found an average of 42.6 repetitions and Plyley *et al.* (1985) observed a range of 42 to 62 repetitions, suggesting elite sailors have a high level of trunk endurance in a dynamic non-hiking specific task. Larsson *et al.* (1996) examined isometric endurance of anterior, posterior and lateral trunk muscles in elite male and female sailors compared to well-trained male control in horizontal positions with support at the iliac crest, pelvis and legs. No differences were found between groups, however the hikers within the male sailing group tended to score better reaching significance in the left side only ($P < 0.05$), possibly highlighting the specificity of hiking in the strength-endurance of the trunk musculature.

The majority of strength-endurance research in hikers have utilised tasks using hiking benches or specifically designed boat simulators that are more representative of the sailing demands in terms of positioning and muscle action (Larsson *et al.,* (1996). As may be expected, hikers typically outperform controls and non-hiking sailors in these tasks. Larsson *et al.* (1996) constructed a hiking bench (Figure 2.8) with the toe strap connected to a strain gauge transducer accurate to ± 5 N, and conducted an isometric trial at 75% hiking MVC, and a dynamic trial with the same load, but with participants performing hiking movements within 35 – 60° of flexion at the hip at a rate of 60 per minute to exhaustion. In both trials elite male hikers recorded greater time to exhaustion to elite male non-hikers and male controls Non-hikers and controls were similar, and interestingly female sailors tended to be better than both of these groups (isometric: hikers 218 ± 38, non-hikers 98 ± 12, controls, 107 ± 16, female sailors 153 ± 21 sec; dynamic: hikers 160 ± 26, non-hikers 83 ± 8, controls 80 ± 10, female sailors 106 ± 19 sec).

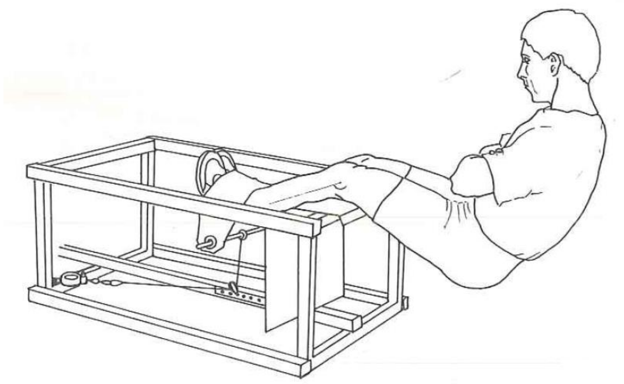

Figure 2.8 Body positioning during a hiking-specific task using a hiking bench (taken from Larsson *et al*., 1996)

Vangelakoudi *et al.* (2007) investigated the hiking strength-endurance of national and club level Laser sailors using an ergometer where sailors hiked on a platform counterbalanced with free weights on the opposite side to maintain a horizontal position, sailors were required to hike for three minute bouts with five sec rest intervals to relieve discomfort, the test was terminated when the sailor couldn't keep the platform horizontal. National ranked Laser sailors maintained the horizontal position for approximately two and a half times longer than the club level sailors (1381 vs. 565 sec), during the trial both groups worked at similar intensities (elite 45 ± 4, club 47 ± 10 % MVC) and terminated the trial at similar cardiovascular responses in heart rate (elite 149 ± 22, club 149 ± 21 beats·min^{-1}) and mean arterial blood pressure (elite 129 ± 16, club 120 ± 21 mmHg) the authors suggest that the adaptation in the higher ability sailors may be peripheral in that highly trained hikers are able to cycle recruitment of muscle groups more efficiently thus enhancing endurance time.

In support of the suggestions of Vangelakoudi *et al.* (2007), the neuromuscular responses of hiking have been investigated which identified a difference in the neural distribution of synergistic muscle groups in hikers compared to non-hikers and controls (Maisetti *et al.,* 2005). In this study participants performed a hiking trial to exhaustion on a simulator designed to replicate moderate wind strength hiking based on the work of Blackburn (1994), positioning set-up was 110° and 140° at the hip and knee. A hiking MVC was performed on the simulator at the joint angles described above, the endurance trial was conducted at 50% of MVC. Electrical activity of the hiking musculature was measured using sEMG attached to abdominals, quadriceps and ankle dorsiflexor muscles, RMS and MPF were analysed to determine muscular contributions and the degree of fatigue. MVC was not different between groups matched for height and body mass, the hikers were able to hold the position for approximately 45% longer than other groups (hikers 344 ± 37, non-hikers 236 ± 23, controls 238 ± 14 s). The abdominals exhibited twice the level of fatigue across all groups evidenced through a greater shift in MPF, indicating the importance of abdominal fatigue resistance in moderate wind hiking. The authors speculate that the increase endurance times in hikers was due to adopting a more efficient alternate-leg pattern of force (improved technique) and a delayed recruitment of additional motor units compared to the other groups. Hikers also differed in the synergistic pattern of recruitment, favouring the quadriceps possibly to minimise the use of the more fatigable trunk flexors, signifying the specific adaptations of hikers to prolong endurance in the hiking position.

Upper body endurance was measured during simulated hiking on a hiking bench by Larsson *et al.* (1996) using an arm ergometer which consisted of a mainsheet attached to a flywheel using wind resistance. Participants performed 60-seconds of maximal repeated elbow flexion movements in the hiking position to simulate the upper body demands of hiking, work output was recorded as the greatest number of flywheel revolutions (revs). Elite sailors (consisting of hikers and non-hikers) performed better than controls on the left arm (737 ± 20 vs. 679 ± 20 revs), and hikers produced greater work than non-hikers on both arms (left arm 756 ± 20 vs. 716 ± 28, right arm 788 ± 20 vs. 717 ± 20 revs), possibly highlighting the increased upper body endurance in a sailing population and the specificity of the task towards hiking sailors.

2.5.1.4 Aerobic fitness

Measurements of the maximal rate of oxygen uptake ($\dot{V}O_{2max}$) of elite hikers have varied considerably over the past 30 years. Early research from the mid-1980’s found only moderate values, however more recent studies have expressed higher markers of aerobic fitness (Table 2.4). Bojsen-Möller *et al.* (2014) cite the increased level of competition in sailing in recent years as a contributing factor to the increased aerobic demand, and that historically it was possible to achieve a high level of sailing without a great level of physical capacity. In support of this statement, when classifying participants in the methods section of Niinimaa *et al.* (1977) study, eight out of the ten were reported as lifetime non-smokers, with one elite sailor reporting smoking 20 cigarettes a day. It must be acknowledged that there are different levels of physical demand across different hiking classes (Bojsen-Möller *et al.,* 2007), hiking classes only are displayed in Table 2.4 apart from Larsson *et al.* (1996). It is evident from the studies presented in Table 2.4 that the aerobic fitness of hiking sailors is comparable with team sport players, though is considerably less than endurance athletes which is supported by Bojsen-Möller *et al.* (2007) who go on to conclude that once a good level of aerobic fitness is achieved then maintenance should be the focus, allowing more time to focus on other parameters of performance.

Table 2.4 Maximal rate of oxygen uptake of sailors in studies from 1985 to 2015.

Study	Class of sailors	Maximal oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$)
Plyley *et al.* (1985)	Finn, 470, Flying Dutchman, Star	*Predicted* 48.2 (range 46.0 – 51.3)
Blackburn (1994)	Laser	62.3 ± 8.2
Vogiatzis *et al.* (1995)	Laser	52.0 ± 6.0
Larsson *et al.* (1996)	Males: Finn, Star, Laser, 470, Tornado*, Flying Dutchman Females: Europe, 470, Lechner Sailboard*	63.8 ± 1.7 (males) 50.1 ± 1.4 (females)
Bojsen-Möller *et al*. (2007)	Male Static: Finn, Star Male Dynamic: Laser Female Dynamic: Europe	47.6 – 63.3 58.3 – 60.4 47.3 – 51.7
Cunningham and Hale (2007)	Laser	55.7 ± 4.0 (range 50.1 – 60.3)
Bourgois *et al.* (2015)	Laser	57.1 ± 4.2

Note: Plyley *et al*. (1985) used a submaximal cycle test to predict $\dot{V}O_2max$.*Non-hiking classes

The aerobic demand of hiking has been contested in the literature, with a range of values of oxygen consumption ($\dot{V}O_2$) being measured in on-land and on-water studies. There is agreement that hiking involves a degree of quasi-isometric and dynamic action, although the relative contributions of these actions are still debated. Spurway (2007) published a review on the physiology of hiking and concluded that the predominant loading was from quasi-isometric action and this comprised approximately half of the overall metabolic cost, this was supported by the on-water study of Vogiatzis *et al.* (1995) who investigated Laser sailors from the Scottish National squad using Cosmed K4 portable gas analysers under dry suits, found $\dot{V}O_2$ values of 22 $mL \cdot kg^{-1} \cdot min^{-1}$ which equates to approximately 42% $\dot{V}O_2max$. Blackburn (1994) developed a simulator based on video from on-water Laser sailing in top Australian sailors, and found that $\dot{V}O_2$ values rarely surpassed 30% $\dot{V}O_2max$. Further evidence to the greater presence of the low to moderate aerobic cost and predominantly quasi-isometric action is the disparity in heart rate and $\dot{V}O_2$ measured in these studies. This is displayed in Figure 2.9 from the work of Vogiatzis *et al.* (1995). It is expected that in purely dynamic exercise, such as cycling, that the two lines in the graph would nearly overlap therefore hiking cannot be purely predominantly dynamic. Spurway (2007) indicates that observing greater relative heart rates to $\dot{V}O_2$ is typical of the physiological response to isometric work, as a disproportional creation of metabolites to oxygen need increases central drive to muscles that are inadequately perfused and under great intramuscular pressure.

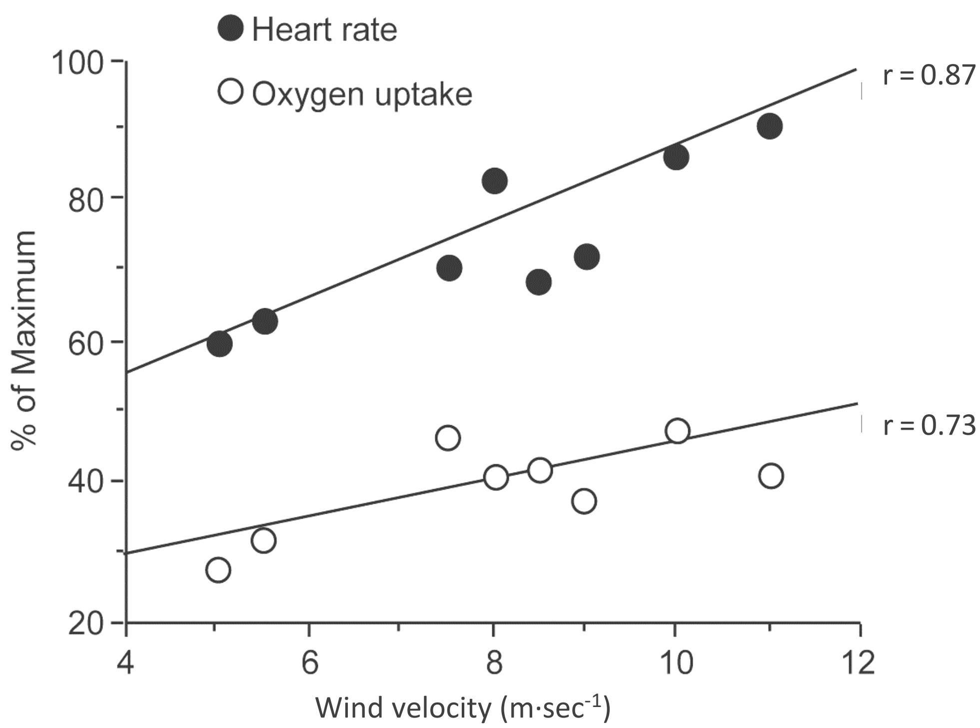

Figure 2.9 Heart rate and $\dot{V}O_2$ measured at different wind speeds during on-water hiking (taken from Vogiatzis *et al.,* 1995)

Contrary to these findings are data from studies by Cunningham and Hale (2007) and Castagna and Brisswalter (2007). These studies measured hiking $\dot{V}O_2$ demands of up to 58.1% and 68% $\dot{V}O_2max$ respectively, summarising that elite level hiking requires a much higher dynamic component than first thought and therefore a greater aerobic requirement. Reasons for this discrepancy put forward by Cunningham and Hale (2007) include: the use of non-elite sailors and data collected from training rather than racing (Vogiatzis *et al.,*

1995) and on-land simulations being too static in nature and more representative of lower wind strength (Blackburn, 1994). It has been previously stated in this chapter that higher sailing ability level results in improvements in hiking time to exhaustion, with differences in technique and cycling of muscle activity being cited as main determinants (Maisetti *et al.,* 2006). This added dynamic element is necessary for increasing boat speed as hikers use additional whole body movements to move more efficiently through waves and can result in producing a greater aerobic demand, supported by Spurway *et al.* (2000) who reported higher femoral vein lactate production when added dynamic movements were added to isometric knee extension bouts of three minutes (see Figure 2.10). Cunningham and Hale (2007) do not rule out the contribution of an isometric action as the mean minute ventilation ($\dot{V}_E$) observed in hiking at 58% $\dot{V}O_2$peak was comparable to 97.2% during the cycle ergometer trial, which agrees with the thoughts of Spurway (2007) and Vogiatzis *et al.* (1995) on a disproportionate central drive above oxygen requirement.

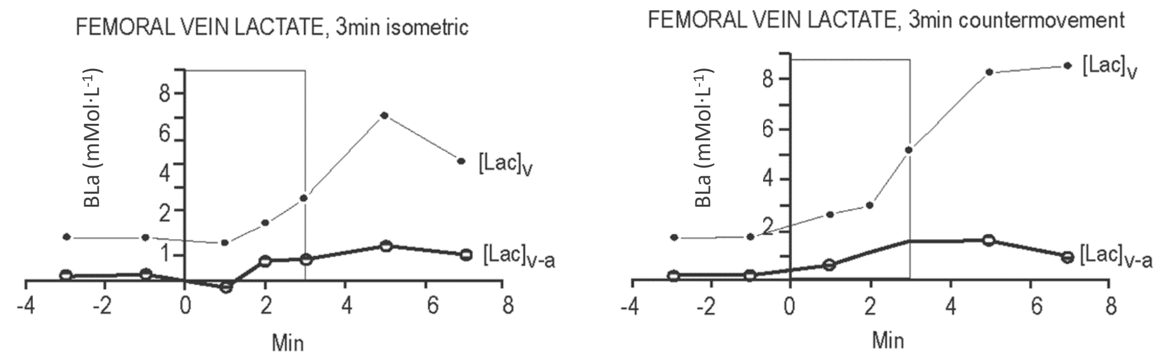

Figure 2.10 Femoral vein lactate production in two knee extension trials at 25% MVC. The left graph is isometric, the right includes dynamic movements of ± 0.17 radians (taken from Spurway *et al*., 2000). Note: Bla – blood lactate concentration, [Lac]v – femoral vein lactate concentration, [Lac]v-a – arterio-venous difference

Castagna and Brisswalter (2007) cite the duration of hiking as another potential reason for the low aerobic cost reported in previous studies, as after ten minutes of hiking (comparable to duration of Vogiatzis *et al.,* 1995) they measured similar values (42.5% vs. 39.0% $\dot{V}O_2$max), at 30 minutes greater demand was observed plus an increase was seen in higher level and potentially more dynamic sailors (high skilled 68.35 ± 1.76 %, low skilled 51.29 ± 1.38% $\dot{V}O_2$max). As races at elite level can comprise 45-60 minutes with at least 75% of this time (30 – 45 mins) hiking upwind, a longer duration witnessed in this study is more ecologically valid therefore it appears the aerobic requirement in hiking is greater than first thought.

2.5.1.5 Other physical characteristics

It is clear from an increase in forces observed in the toe strap and mainsheet that higher wind speeds result in greater physical demand in hiking classes (Mackie *et al.,* 1999), in these conditions there is a correlation between wind strength and the anaerobic capacity of the sailor (Niinimaa *et al.,* 1977). A number of studies have shown relationships between the performance level of the sailor and anaerobic capacity (Niinimaa *et al.,* 1977; Vangelakoudi *et al.,* 2007) which is proposed to be due to the ability to produce high amounts of force for short periods to increase boat speed by optimising boat pitch in gusty and wavy conditions (Mackie *et al.,* 1999). The Vangelakoudi *et al.* (2007) study had elite and club level Laser sailors perform Wingate tests to establish indices of anaerobic power. The authors found no difference between the two groups in peak power and mean power, but found a strong negative correlation between these markers and national ranking (r = -0.71, -0.83). Mean power (8.0 ± 0.63 $W \cdot kg^{-1}$) in Laser sailors was found to be comparable to team sport players (8.2 ± 0.1) and long distance runners (8.0 ± 0.1 $W \cdot kg^{-1}$), peak power recorded (11.0 ± 0.2 $W \cdot kg^{-1}$) was similar to swimmers (11.1 ± 1.06 $W \cdot kg^{-1}$) and middle distance runners (10.5 ± 0.1 $W \cdot kg^{-1}$). The elite group though had an improved fatigue index calculated as end power as a percentage of peak power (42.5 ± 5.0 vs. 49.0 ± 6.0 %).

Other physical requirements of hikers include balance, which was found to be correlated to performance in high winds (r = 0.6) and to competitive success and captain's ranking in the study of Niinimaa *et al.* (1977) (r = 0.72) and agility (Bojsen-Möller *et al.,* 2014) (r = 0.66) although this has not been investigated in elite hikers to the author's knowledge.

2.5.1.6 Trapeeze sailors

Purely static on-land simulations of trapeezing have revealed only moderate physical demand (Marchetti *et al.,* 1980) although this doesn't represent actual on-water sailing (Besier and Sanders, 1999). Trapeeze sailors wear a harness that is attached to the mast, which offloads some of the gravitational loading on the spine while being in a horizontally extended position for long periods. Trapeezing sailors are required to perform a number of body movements, fore and aft (lateral) movements to enable effective sailing through waves or explosive anterior-posterior movements for propulsion or more subtle control while adjusting for gusts and lulls in wind strength. The most physical of these movements in the 470 class is termed 'body pumping' where the sailor vigorously flexes and extends the spine while pushing with the legs and pulling with the arms to maximise speed upwind, when sailing downwind within the rules the 470 crew crouches on the side of the boat and fans the larger spinnaker sail using repetitive powerful upper body pulling movements. The most physically demanding action for trapeeze sailors in the higher performance 49er skiff and Nacra-17 catamaran is hoisting and dropping the large spinnaker sail downwind, due to high tension loading on the rope and the need to completing this as fast as possible to maximise accelerations and reducing deceleration around the race course. This is performed in a quarter squat by powerfully pulling the rope up in repeated single arm movements from ankle height to above head level.

Very few studies exist on the physical requirements of trapeeze sailors, even fewer using an elite cohort. There are also difficulties with using the non-hikers in research, unless trapeeze sailors are specifically identified, as the group frequently contains a mixture of trapeeze and board sailors plus side hikers that are supported with a strong harness, all these sailing positions have different physical and anthropometrical requirements (Bojsen-Möller *et al.,* 2007) and therefore cannot be compared.

When investigating the strength and strength-endurance in elite trapeeze sailors early research identified similar maximal handgrip strength (trapeeze 57.3 kg, hikers 56.9 kg) and trunk endurance, measured by number of sit-ups in 60 seconds (trapeeze 47 – 59, hikers 42 – 62 repetitions), than in hikers (Niinimaa *et al.,* 1977). It must be acknowledged that this was in a very small sample of trapeeze sailors (n = 4). Maisetti *et al.* (2006) recorded maximal hiking contraction in elite hikers and 49er crew (trapeeze) sailors, although insignificant 49er crew sailors produced greater maximal force at 1520 ± 7 Nm vs. 1340 ± 8 Nm (S.E.), though when 50% MVC was performed to exhaustion the trapeeze sailors had significantly poorer times (236 ± 23 vs. 344 ± 37 sec). During trapeezing sailors are supported by a harness which decreases the muscular load on the trunk (Marchetti *et al.,* 1980) which may explain the decreased strength-endurance performance in a hiking trial where the abdominals fatigue at twice the rate of the quadriceps (Maisetti *et al.,* 2006). Besier and Sanders (1999) however state that trunk flexors and extensors are physically taxed in light winds (35 – 40% MVC) where crews are crouched inside the boat and the harness does not support their weight. Even during supported trapeezing trunk and knee extensor activation may increase above 45% MVC depending on the degree of dynamic movement and technique adopted (e.g. holding one arm above head to increase righting moment). Besier and Sanders (1999) summarise that trapeeze sailing, especially during the dynamic action of body pumping produces significant anterior/posterior and rotational stresses to the musculoskeletal system, mainly through the rapid accelerations and eccentric contractions of the trunk, which may increase risk of injury through fatigue when completing multiple races.

Maximal aerobic fitness in elite trapeeze sailors have followed a similar trend to the elite hikers, with earlier research findings demonstrating a lower requirement in comparison to recent data (Table 2.4). Plyley *et al.* (1985) found predicted $\dot{V}O_2max$ values of Tornado sailors (Olympic catamaran class from 1976 to 2008) of 38.5 to 41.2 $mL\cdot kg^{-1}\cdot min^{-1}$, but much higher in 470 crews (54.7 $mL\cdot kg^{-1}\cdot min^{-1}$). In more recent research Bojsen-Möller *et al.* (2007) reported $\dot{V}O_{2peak}$ in the range of 57.3 ± 3.7 to 64.4 ± 3.7 $mL\cdot kg^{-1}\cdot min^{-1}$ in trapeezing crews, and 55.3 ± 4.0 and 49.5 ± 2.5 $mL\cdot kg^{-1}\cdot min^{-1}$ in trapeezing helms and female crews. This suggests a greater aerobic requirement in more contemporary trapeeze sailing, the authors suggest the constant adjustment in body position and pumping are main determinants for the increased aerobic demand, accompanied with the recovery from high intensity bursts of hoisting and dropping (Bay and Larsson, 2013).

Bojsen-Möller *et al.* (2014) cite the unpublished thesis data of Bay and Larsson (2013) that reported the heavy aerobic and anaerobic demands in elite 49er crews from developing a simulator based on repeated short duration ‘theatre-style’ racing, including the specific movements of trapeezing, hoisting and dropping the spinnaker and trimming the main sail plus tacking and gybing. Three consecutive five minute races were completed which consisted of six maximal hoists/drops using a counterbalanced free-weight system. Peak power output predominantly created from the upper body musculature was recorded at 8 $W\cdot kg^{-1}$ (absolute 580 W), with mean power output of approximately 7 $W\cdot kg^{-1}$ over a 10-second average. A 26% reduction in peak power was observed over the course of the protocol (Figure 2.11) displaying the fatigue encountered in racing and the resultant need for highly developed aerobic and anaerobic systems.

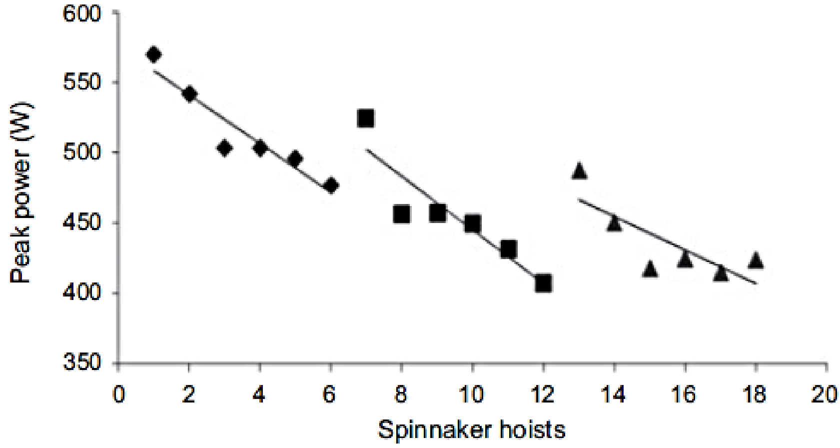

Figure 2.11 Decrease in peak power output (26%) in simulated spinnaker hoists/drops during 3 x 5 minute races interspersed by 5 minute recovery (Bay and Larsson, 2013) taken from Bojsen-Möller *et al*. (2014)

Bojsen-Möller *et al.* (2007) summarised that trapeeze sailors experience a lower isometric loading when compared to hiking, but a significant agility and movement-based demand that must be supported by a well-developed aerobic system. Allen and DeJong (2006) emphasise that more focus should be placed on upper body strength and endurance, agility and aerobic fitness. These statements combined with the lack of research and the relative importance of trapeezing in Olympic sailing evidenced by the increase in trapeeze positions included within the Olympic Games (Figure 1.6) points towards the need for more studies investigating the physical requirements of these sailing positions.

2.5.1.7 Boardsailors

Boardsailing has gone through two significant changes in the last 20 years that have increased the physical demands. In the early 1990s Olympic boardsailing was contested on the Mistral One Design (MOD) racing board, in 1993 unlimited pumping of the sail was introduced within the rules governed by World Sailing, the International governing body for sailing. Before this boardsailing was considered a moderately intense sport. Pumping involves using the whole body to rhythmically push and pull the sail using the boom, which effectively creates a fanning motion that provides forwards propulsion. Pumping is effective in increasing speed while sailing in wind speeds of up to approximately 15 knots, at higher wind speed the additional jump in physical demand would not balance against the minimal speed advantage to continue to pump around the race course, although pumping is still used off the start line to gain tactical advantage and to accelerate the board out of manoeuvres where speed has reduced greatly (Vogiatzis and DeVito, 2014). In 2006 the Mistral One design was replaced as the international racing class by the Neil Pryde RS:X, this increased the sail area from 7.5m^2 to 8.5m^2 for females and to 9.5m^2 for males (termed in this thesis as RS:X 8.5m and RS:X 9.5m). This significantly increased the amount of wind power to be harnessed, and therefore the physical demand required to propel the board increased (Castagna *et al.,* 2007). A diagram presenting the most effective upwind pumping (UWP) technique of the RS:X is shown in Figure 2.12.

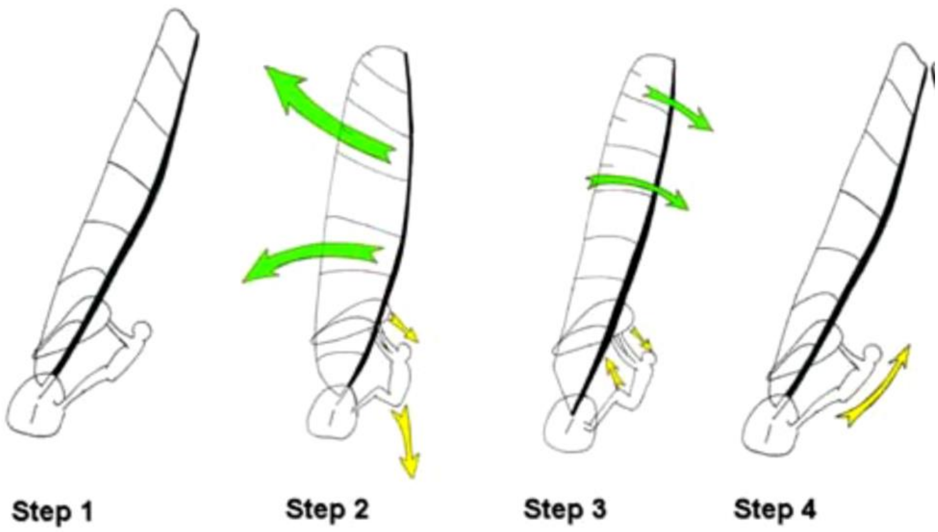

Figure 2.12 Pumping technique in the Neil Pryde RS:X racing board (taken from Castagna et al., 2007). Note: Green arrows = sail movement, yellow arrows = body movement: Step 1 – arms close to body with legs extended, Step 2 – knees bend as body drops away from sail, arms are extended as sail comes away from the body. Steps 3 to 4: sailor pulls violently on the boom combined with explosive hip and knee extension returning to the starting position.

Research into the strength and muscular requirements of Olympic boardsailing has focused on the MOD race board, early work from Dyson *et al.* (1996) and Buchanan *et al.* (1996) measured EMG activity during on-water and simulated boardsailing with six national or international boardsailors (three male and three female). Dyson *et al.* (1996) reported different timings and magnitudes of muscular activity between participants, possibly due to differences in technique and on-water conditions. Muscle groups that were highlighted as more active were: flexor and extensor carpi ulnaris, trapezius, biceps brachii, tibialis anterior and gluteus maximus. Buchanan *et al.* (1996) found increased upper body physical demands in pumping, but specifically in downwind pumping (DWP) (upper body 72 ± 6 vs. 62 ± 6%, lower body 27 ± 3 vs. 25 ± 3% MEVC). During DWP the sailor adopts a more central position on the board and needs to physically push the sail away to the windward side of the board before initiating the pulling/extending movement (Buchanan *et al.,* 1996; Dyson *et al.,* 1996). Specifically muscles involved in gripping and pulling the boom typically revealed greater levels of activity in male boardsailors (Table 2.5).

Table 2.5 Activity of grip and pulling musculature in boardsailing pumping. (Values displayed are mean %MEVC ± S.E.) (Buchanan *et al*., 1996).

	Sailing direction	ECR	BB	LD
Male	UWP	83 ± 12	90 ± 5	50 ± 9
	DWP	105 ± 1	94 ± 3	87 ± 9
Female	UWP	81 ± 5	74 ± 13	31 ± 4
	DWP	84 ± 7	68 ± 14	47 ± 7

Note: ECR – Extensor Carpi Radialis, BB – Biceps Brachii, LD – Latissimus Dorsi, UWP – Upwind Pumping, DWP – Downwind Pumping

Mean heart rates measured during pumping on the MOD boardsailing simulator in the study of Buchanan *et al.* (1996) of 113 ± 9 and 125 ± 9 beats·min^{-1} in UWP and DWP respectively, were lower than on-water MOD pumping in the findings of Dyson *et al.* (1996) with mean values ranging from 145 ± 4 to 173 ± 4 beats·min^{-1}, or Vogiatzis *et al.* (2002) recording 163 ± 12 beats·min^{-1}. This highlights the potential limitations of using simulators to recreate on-water performance, however Buchanan and colleagues cite the lack of psychological stress/demand as a potential factor to explain the difference. It should also be noted that the MOD has a less stiff sail and rig accompanied with a 28% smaller sail area than the current Olympic RS:X board therefore a greater level of physicality should be expected. This is supported in more recent studies that state RS:X pumping technique involves vigorous and explosive whole body movement that involves a great amount of muscular activity, and that the physical demands require upper and lower body strength training to improve performance (Castagna *et al.,* 2008; Vogiatzis and De Vito, 2014).

Olympic boardsailing has been described as "a very demanding endurance sport activity…can be considered as a high-intensity endurance type of sport that is comparable to other aerobic activities such as rowing" (Vogiatzis and De Vito, 2014, p.1). High levels of $\dot{V}O_2max$ are observed in elite level boardsailing from: 63 ± 6.2 (Vogiatzis *et al.*, 2002; Vogiatzis *et al.*, 2005), 63.7 ± 4.2 (Castagna *et al.,* 2007) to 65.1 ± 5.9 mL·kg^{-1}·min^{-1} (Castagna *et al.,* 2008). Aerobic demands of boardsailing in the MOD and RS:X race boards are displayed in Table 2.6, note the lower values recorded when boardsailing upwind in 17-

21 knots of wind speed as pumping only consists of 37.5 ± 8% of time in comparison to approximately 65-70% during upwind boardsailing in 4-8 knots or downwind boardsailing in both conditions (Castagna *et al.,* 2007).

Table 2.6 Aerobic demands of Olympic boardsailing in MOD and RS:X race boards.

Author(s) / Wind strength	Board	Sailing direction	% $\dot{V}O_2max$	% HR_{max}	[La] (mmol.L^{-1})
Vogiatzis *et al.* (2005)	MOD	UWP	77 ± 8	87 ± 8	3.7
		DWP	81 ± 9	89 ± 11	4.5
Castagna *et al.* (2008) 4 to 8 knots	RS:X	UWP	83 ± 3	89 ± 2	9.7 ± 2.8
		DWP	87 ± 2	93 ± 4	10.2 ± 1.5
Castagna *et al.* (2008) 17 to 21 knots	RS:X	UWP	62 ± 9	67 ± 8	5.0 ± 2.7
		DWP	85 ± 5	91 ± 3	9.6 ± 2.3

Note: UWP – Upwind Pumping, DWP – Downwind Pumping.

During conditions when pumping does not provide added speed benefit, the intensity and physical demand reduces as the board is propelled forwards using a similar *quasi-isometric* action to hiking (Van Gheluwe *et al.,* 1988; Vogiatzis and DeVito, 2014). Similar to hiking, heart rate remains disproportionately higher than $\dot{V}O_2$ during non-pumping boardsailing (56 ± 5% HR_{max} vs. 30 ± 3% $\dot{V}O_2max$; Vogiatzis *et al.,* 2002) reflecting an inability of oxygen perfusion at the muscle. The board sailor attaches themselves to the boom using a harness worn around the waist and involves maximising the righting moment by leaning away from the sail, using the forearms, trunk and legs forcefully to maintain this distance against the power of the rig while surfing over waves and constantly adjusting for changes in wind strength (Castagna *et al.*, 2008).

2.5.1.8 Anthropometry

As can be seen in the self-reported sailor information from the Rio 2016 Olympic data feed (Figure 2.13), there is a great range in anthropometrical characteristics in Olympic sailing, females range from approximately 56 kg and 163 cm to 70 kg and 176 cm, males from approximately 65 kg and 174 cm to 97 kg and 192 cm. This is predominantly explained by the differences in positional and class demands relative to the boat/board, and double-handed boat crew positions looking to maximise their righting potential to optimise boat speed and performance (Bojsen-Möller *et al.,* 2007).

An example of maximising righting moment is the double-handed female 470 class where the helm height/body mass is approximately 163 cm/56 kg, the crew 176 cm/70 kg. In this class the helm hikes and the crew trapezes, to maximise righting moment when considering the amount of the body that is able to be utilised out of the side of the boat in trapeezing versus hiking (whole body versus upper body respectively) it would be beneficial to maximise body mass and height in the crew, while keeping the body mass as low as possible in the helm. This effectively ensures total body mass doesn't become too high and slows the boat down by displacing more water. A photo of the 470 can be seen in the middle image in Figure 1.3 with the helm hiking and crew trapeezing.

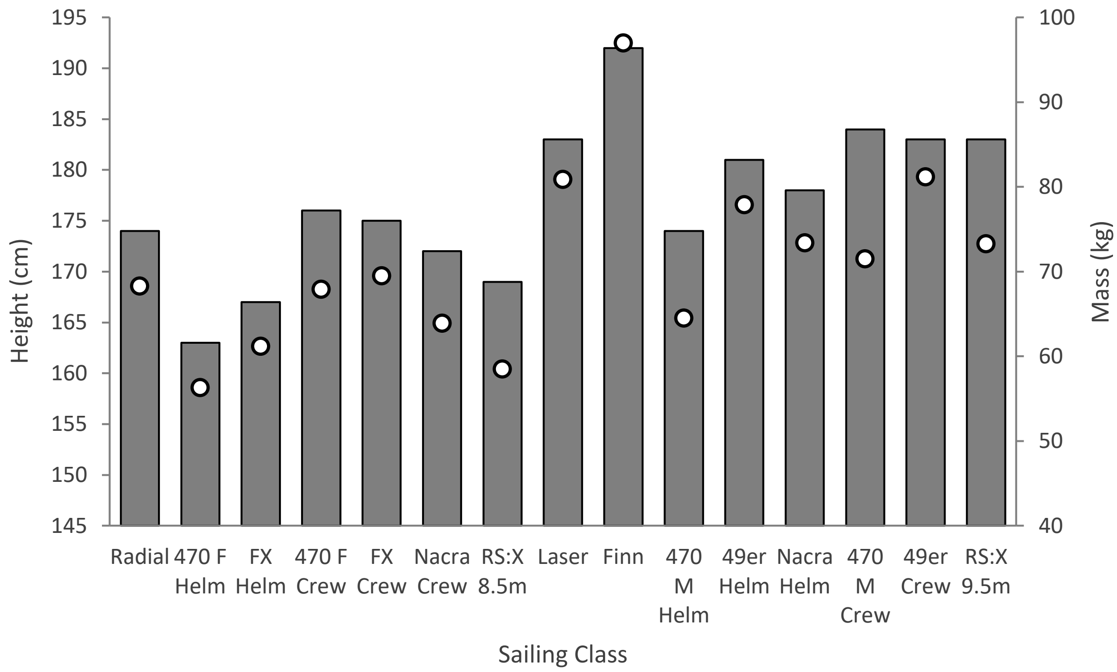

Figure 2.13 Mean Height (cm) and body mass (kg) in Rio 2016 Olympic classes (Olympic.org, n.d.2). Note: Heights represented as bars, body mass as circles, F – female, M - male

The other main explanation for differences across classes is due to the physical requirements in sailing the boat/board, Mackie *et al.* (1999) found that greatest hiking and sheeting forces were evident in the Finn class compared to Laser and 470. It is clear from the heeling moment relationship with sail area that more force will be generated from larger sails therefore requiring more righting moment from the sailor (s) to keep the boat flat, which mainly consists of a greater requirement in body mass and physicality (Bojsen-Möller *et al.,* 2014).

2.5.2 Pathway sailing

Very few studies have investigated elite sailing below adult Olympic level, no research has involved double-handed boats or board sailors with the focus being placed on the hiking positions in the Laser, Laser Radial, Byte and Optimist classes. As has been presented earlier in this thesis, the number of hiking positions in Olympic sailing has reduced in recent years and constituted six out of 15 positions in the Rio Olympics (Bojsen-Möller *et al.,* 2014), therefore the lack of trapeeze and boardsailing research in Youth sailing is a concern. Conversely other sports have received plenty of research attention at Youth level, in particular football (Gonaus and Müller, 2012; Malina *et al.,* 2005; Philippaerts *et al.,* 2006; Reilly *et al.,* 2000; Vaeyens *et al.,* 2006;), handball (Matthys *et al.,* 2013a; Matthys *et al.,* 2013b) and swimming (Allen *et al.,* 2014). This section will be split into sailing-specific and non-specific physical attributes of elite Youth sailors

2.5.2.1 Sailing-specific physical attributes

One of the earliest studies investigated indicators of performance in national-level Laser and Laser Radial Youth sailors competing in the Singapore National Inter-school Laser Championships (Tan *et al.,* 2006). Twenty boys and fifteen girls (mean age ± S.D. (range) 17.7 ± 0.6 (16.0 to 18.5) vs. 17.9 ± 0.7 (16.7 to 19.3) years; mean sailing experience ± S.D. (range) 3.5 ± 2.2 (1.0 to 8.0) vs. 3.6 ± 2.7 (1.0 to 10.0) years) participated in sailing-specific strength and strength-endurance tests. This included the maximal hiking moment over three mins (HM_{180}) performed on a specifically designed hiking bench affixed to a force platform – this test has been used in more recent Youth sailing research (Burnett *et al.,* 2012). In male Laser sailors, HM_{180} was strongly correlated to finishing position in the championships ($r = -0.62$, $P < 0.01$), knee extension 3RM and quadriceps endurance (measured by repetitions to failure using 40% of knee extension 3RM) were found to be moderately correlated to sailing performance ($r = -0.47$ and -0.51 respectively, $P < 0.05$). No relationships existed between female sailors and performance, the reason highlighted by the authors was due to sailing conditions (8-12 knots) not taxing hiking enough in the smaller Laser Radial boat. On dry land however knee extension 3RM and an isometric knee extension MVC were found to be correlated with HM_{180} performance ($r = 0.81$ and 0.87 respectively, $P < 0.05$).

Burnett *et al.* (2012) examined if the HM_{180} could discriminate between sailing performance level and gender between the Singaporean National Byte squad against a lower level high-participation group (boys 14.1 ± 0.7, girls 14.3 ± 1.0 years), groups were not statistically different apart from body mass being higher in the national squad group (*P* < 0.05) and the national squad had >1 year sailing experience with a greater training volume (8 sessions week and a minimum of six months resistance training vs. three sailing sessions a week with no structured resistance training). The HM_{180} performance was higher in the national squad group and in boys versus girls (*P* < 0.05) highlighting the importance of hiking-specific training volume/experience, it should be noted however that body mass was greater in the national squad group which was correlated to HM_{180} performance (r = 0.95 to 0.97, *P* < 0.01; Tan *et al.,* 2006). The authors conclude that Youth sailors should engage in strength and conditioning exercises of the knee extensors and trunk to enhance hiking performance.

Knee extensor strength-endurance has been measured in a Junior and Youth sailing population using the Bucket test (Callewaert *et al.,* 2014b; Tan *et al.*, 2006) in which the participant sits off the edge of a bench with knees extended and a bucket with progressively heavier loads placed around the ankles. The exact protocol has been modified for younger sailors from the original test described by Blackburn (2000), with a reduced starting load - 15 kg (0 kg in the bucket) though both protocols increment the load by 5 kg each minute until the participant cannot maintain a knee angle of ≥ 130°. Callewaert *et al.* (2014b) investigated the indicators of different levels of Youth sailing performance in two groups of Flemish dinghy sailors: Optimist (12.3 ± 1.4 years) and 'dynamic' hikers who sailed the Laser 4.7, Laser Radial and Europe boats (16.5 ± 1.6 years). Performance in the Bucket test differentiated between elite and non-elite sailors in Optimist (301.3 ± 67.7 vs. 409.4 ± 51.1 sec, *P* = 0.002) and 'dynamic' hiking classes (490.3 ± 64.7 vs. 600.1 ± 40.9 sec, *P* = 0.050) and accounted for 89% of performance in 'dynamic' hiking performance level by means of multivariate analysis of covariance and discriminate analysis. Tan *et al.* (2006) reported a moderate correlation between Bucket test performance and HM_{180} in males (r = 0.53, *P* < 0.01), but not with females or on-water performance. With the limited amount of research it is difficult to ascertain the relationship between Bucket test performance and Junior and Youth sailing performance, however the preliminary findings support this link in the majority.

An upwind sailing ergometer was constructed by Callewaert *et al.* (2013a) to replicate the conditions of upwind sailing, this ergometer was then used to investigate the cardio-respiratory and muscular responses in Youth Optimist sailors to hiking (Callewaert *et al.,* 2013b). The protocols employed consisted of twelve to seventeen bouts of 90 sec quasi-isometric hiking separated by 10 sec to simulate a tack, each 90 sec bout required participants to hike at varying intensities (e.g. light hiking, hard hiking). Good overall feedback was given on the similarity of the ergometer protocol to on-water sailing using a 1 to 5 Likert-scale (1 -very bad, 2 - bad, 3 - moderate, 4 - good, 5 - very good), hiking position/intensity and loading in the rudder and mainsheet were all scored as good (4.0 ± 0.8, 4.0 ± 0.8, 4.3 ± 0.8 and 4.6 ± 0.7 respectively), moderate scores were given for fatigue and tacking (3.0 ± 0.5, and 2.5 ± 1.0) and a bad results for boat tilt (1.7 ± 0.7) (Callewaert *et al.,* 2013b). International Youth male Optimist sailors were tested over 12 bouts compared to untrained males matched for age, height and body mass, knee extension MVC torque at 120° knee and hip angle was not different between groups (151 ± 43.9 vs. 153.3 ± 55.3 Nm) however the international Optimist sailors were more fatigue resistant at the muscular level displayed by a slower rate of increase in RMS and decrease in MPF plus a decreased reduction in MPF at the last bout of the protocol (99.3 ± 5.0 vs. 88.9 ± 5.7%, $P < 0.001$) (Callewaert *et al.,* 2013b). The authors contend that trained sailors are able to extract greater levels of oxygen at the capillary level, due to a greater amount of slow twitch muscle fibres. This is predominantly evidenced through increased levels of deoxygenated haemoglobin and myoglobin (Deoxy [Hb+Mb]) (142.3 ± 18.5 vs. 124.4 ± 7.8%, $P < 0.05$), and are able to recruit less additional more fatigable fast twitch fibres towards the end of the protocol although this was not significant.

2.5.2.2 Non-specific physical attributes

Non-specific physical attributes have been measured in elite and non-elite Optimist and ‘dynamic’ hiking sailors (Callewaert *et al.,* 2014b). Within the Optimist group 100% of sailor performance level was differentiated by motor co-ordination tests of side-stepping (difference between performance level $P = 0.008$) and side jumping ($P = 0.017$). Elite ‘dynamic’ hiking sailors outperformed the non-elite group in a 5 m sprint ($P = 0.039$) and 20 m aerobic shuttle run ($P = 0.030$). Callewaert *et al.* (2014a) measured aerobic capacity of ten elite Flemish Optimist sailors (age range 10.8 – 14 years), mean score for boys and girls were 57.0 ± 3.1 and 47.3 ± 1.8 $mL \cdot kg^{-1} \cdot min^{-1}$ respectively, boys scores were comparable to elite football players (59.2 ± 3.2 $mL \cdot kg^{-1} \cdot min^{-1}$; Le Gall *et al.*, 2010) and greater than elite volleyball players (43 ± 6.1 $mL \cdot kg^{-1} \cdot min^{-1}$; Gabbett *et al.,* 2007).

The EUROFIT testing battery (Council of Europe, 1988) was developed to assess the physical development of school-aged children in Europe using simple and inexpensive tests (Table

2.7 and Table 2.8), though the protocols can also be used in sporting or medical settings. A number of studies have utilised aspects of the EUROFIT testing battery to profile fitness parameters in school children (Deforche *et al.,* 2003) and Youth athletes competing in Handball (Matthys *et al.,* 2013a) and Football (Vaeyens *et al.,* 2006). Callewaert *et al.* (2014b) used the same testing battery to investigate indicators of Junior and Youth sailing performance between performance level, the results of the EUROFIT battery of the studies mentioned are presented below (Table 2.7 and Table 2.8). Elite Optimist sailors produced lower handgrip force than age-matched handball players, lower aerobic/upper body endurance and similar lower body power compared to football players. Optimist sailors outperformed a non-obese school population in all the above mentioned tests except lower body power. Elite 'dynamic' hiking sailors were slightly older than the equivalent football players, but age-matched to the non-athletic group (Table 2.8). The elite 'dynamic' hiking sailors performed better than the non-athletic group across all tests displayed, and better and similar versus football players in the standing long jump and aerobic/upper body endurance respectively.

The results of non-specific fitness testing within Youth sailing should be viewed with caution, as the authors allude to the possibility that difference in physical performance may be due to participation in other sports and not predominantly sailing volume (Callewaert *et al.,* 2014b). Elite Optimist and 'dynamic' hiking sailors in this study performed on average 9.8 ± 2.2 and 11.6 ± 4.1 hours/week of sailing practice, therefore it is likely that other physical activity was being performed during the week.

Table 2.7 Non-specific physical attributes of elite male Youth Optimist sailors compared to age matched groups

	Callewaert *et al.* (2014b)	Matthys *et al*. (2013a)	Vaeyens *et al*. (2006)	Deforche *et al.* (2003)
Sample (n, age characteristics)	Elite Optimist sailors n = 7, 13.6 ± 1.1 years	Elite handball n = 14, U14	Elite football players, n = 32, U14	Non-obese school, n = 444, 12 – 13 years
Handgrip MVC (kg)	31.4 ± 4.0	41.3 ± 11.5		27.2 ± 7.0
Standing Long jump (m)	1.76 ± 0.13		1.82 ± 0.18	1.75 ± 0.19
Bent-Arm Hang (sec)	27.9 ± 16.9		30.3 ± 18.2	17.6 ± 12.4
20mSRT (min)	8.1 ± 0.8		9.5 ± 1.4	6.6 ± 1.9

Table 2.8 Non-specific physical attributes of elite male Youth 'dynamic' hiking sailors compared to age matched groups

	Callewaert *et al.* (2014b)	Vaeyens *et al.* (2006)	Deforche *et al.* (2003)
Sample (n, age characteristics)	Elite 'dynamic' hiking sailors n = 9, 17.5 ± 1.0 years	Elite football players, n = 32, U16	Non-obese school, n = 576, 16-18 years
Handgrip MVC (kg)	54.6 ± 3.6		47.3 ± 8.7
Standing Long jump (m)	2.26 ± 0.24	2.02 ± 0.14	2.11 ± 0.22
Bent-Arm Hang (sec)	40.8 ± 12.6	40.8 ± 16.4	32.7 ± 15.5
20mSRT (min)	11.1 ± 1.4	11.2 ± 1.6	8.2 ± 2.1

To summarise, it appears that elite Youth sailors have higher levels of strength and fatigue resistance in hiking muscles, predominantly the knee extensors, compared to non-elite sailors and are recommended to partake specifically in strength and conditioning training of these muscles (Burnett *et al.,* 2012). Elite sailors possess non-specific physical attributes that exceed a non-obese school population and are comparable to other youth sport athletes in upper body endurance. At a younger age sailors were found to have lesser handgrip force than handball players, but greater lower body power than football players, although the football group were slightly younger. Caution however should be applied to these findings as participation in other sports was not measured, therefore fitness scores may be in part explained from other non-sailing training.

2.6 Non-physiological/multi-dimensional aspects of TID/TDE

This thesis focuses on the physical characteristics relating to TDE, however it must be acknowledged that other factors contribute to TID and TDE in elite sport as Williams and Ericsson (2005) stated success in most sports is irreducible to a pre-determined set of skills and attributes, as deficiencies in one area can be compensated for strengths in another. Other factors that have been studied include psychological (Van Yperen, 2009), coach skill assessment (Wiseman *et al.,* 2010; Pion *et al.,* 2016), sport-related motor skill performance (Faber *et al.,* 2016) and multi-disciplinary designs (Reilly *et al.,* 2000; Woods *et al.,* 2016).

Psychological factors such as goal commitment, problem-focused coping behaviours and social support seeking behaviours were able to differentiate 84.6% of successful male academy football players (Van Yperen, 2009). A number of studies have investigated the accuracy of coach skill assessments in predicting performance level, inconsistency has been found in youth hockey where a number of coaches identified key characteristics of performance and then using these as guidelines a combination of coaches and scouts were unable to achieve consistency with 9 out of 13 players being grouped into the top and bottom five positions (Wiseman *et al.,* 2010), similar inconsistencies have lead Pion *et al.* (2016) to question the validity of subjective coach assessment. Faber *et al.* (2016) found table tennis related motor skills of sprinting, throwing a ball and speed while dribbling with a ball as significant factors in predicting male and female elite progression respectively. Unfortunately the prediction lacked accuracy highlighting the difficulty of predicting future performance level at a young age.

A number of authors have investigated TID using a multi-disciplinary design in an attempt to capture a more holistic profile. Reilly *et al.* (2000) discovered the most discriminating factors of playing level in youth football players were agility, ego orientation, anticipation and sprint time. In a recent study in Australian football the predictive accuracy of state or non-state participation the next season was increased from 84-89% using single measures of physical or perceptuo-cognitive factors, to discriminating 95.4% of state players as using a combination of both (Woods *et al.,* 2016).

It is clear that there is no set combination of factors that indicate differentiate elite senior success or between elite and non-elite athletes in all sports. Further investigation into a number of factors was suggested by Rees *et al.* (2016) including: athlete birthplace, recovery and sleep, psychological trauma and grit/resilience, family socio-economic status and genetics (Tucker and Collins, 2012).

2.7 Literature Review Summary

Chapter two has provided a review of the current literature pertinent to the development of physical characteristics within a talent pathway, and specifically to the sport of sailing. It is clear that sporting pathways are considered vital to maintain the steady stream of athletes capable of winning medals at senior level. Talent, and its development is a very complex process based on multiple factors that makes the prediction of future success very difficult, especially from early adolescence, which champions TDE over TID. A number of models exist in TDE, each with strengths and limitations that offer guidelines, not a blueprint to success, to aid support at a more individual level. The additional understanding of physical characteristics to TDE adds objectivity to a subjective environment, plus has been found to underpin future athletic and skill development, decrease the likelihood of injury, and promote wellbeing. Sporting pathways should consider profiling athletes' physical characteristics longitudinally, adding data to the non-linear development of talent, paying specific attention to inter- and intra- individual variation originating from a number of factors, including maturation and compensation effects.

Olympic sailing has been noted of becoming more competitive and physically demanding in recent years, therefore the focus on the 'controllable' of physical preparation is well-placed. The variation evident in sailing adds a unique complexity to the developmental journey; consisting of a range of physical demands across classes and positions reviewed in Chapter 2.5, with different potential trajectories towards an unknown set of Olympic classes once sailors reach senior level.

2.8 Thesis Format

The remainder of the thesis comprises of seven chapters, including four empirical studies working towards the aim of building an objective evidence-based manuscript to help inform the British Sailing Team's Olympic pathway:

Chapter three – a novel evaluation of the key physical characteristics of transition to successful Olympic sailing through inductive content analysis of semi-structured interviews with a sample of experienced top elite coaches and Podium level sailors, including multiple Olympic and World Champions. The aim of this study was to add further context and rationale to the current physical testing battery to assess developing elite sailors and provide grounding for developments in new tests.

Chapter four – details the general methods that occur throughout the thesis, plus describes the current physical testing battery, including newly recorded reliability data and context of suitability from previous research where reliability testing was not possible. This chapter introduces the requirement of a new long-term strength test replacement, as the current testing equipment became discontinued, and the need to confirm a method for tracking maturation status and the prediction of peak adult height.

Chapter five – analyses the reliability, validity and interrelationships between the current upper body strength testing methods and field-based bodyweight strength tests with the gold standard tests of one-repetition maximums and isometric peak force. With the aim to identify the replacement tests to continue the assessment of strength within the Olympic pathway.

Chapter six – the aim of this study was to choose the preferred methods of maturity assessment and predict peak adult height to add to the physical testing battery. Achieved by comparing the accuracy of two non-invasive methods of maturity estimation that are able to predict peak adult height. This study used retrospective elite sailor data, who were measured by trained anthropometrists after attainment of actual peak adult height to assess the accuracy of each prediction method.

Chapter seven – using the complete physical testing battery created through the previous findings in earlier empirical chapters within the thesis, elite pathway sailors were profiled twice per season over a period of four years. Leading to the creation of the first cross-sectional analysis of physical characteristics in Olympic pathway sailing classes using adolescent females and males.

Chapter eight – building on the novel cross-sectional analysis of chapter seven, an individual case study design was used to longitudinally track two female and male sailors who were estimated to be early or late maturers during three seasons including the transition to elite Youth squads, to display the inter- and intra-individual variation experienced compared to chronological and biological age-matched elite population benchmarks using z-scores.

Chapter nine – concludes the thesis with a final summary of the research findings and provides recommendations for the British Sailing Team's Olympic pathway, including future avenues of research that may work alongside the continuing physical profiling testing process outlined in this thesis.

Chapter 3 Key characteristics of developing elite sailors

3.1 Introduction

An increased level of competitiveness has been observed in elite sport, with a more of countries obtaining a greater market share of medals at Olympic and World championship level (DeBosscher *et al.,* 2007; Rees *et al.,* 2016). In recent times sports have seen a greater return of medals from increased investment into the production of successful elite athletes (DeBosscher *et al.,* 2013b; Hogan and Norton, 2000). Examples of this have been the Australian Institute of Sport (AIS) who went from $1.2million to $106million of funding from 1976 to 2000 Olympic cycles moving from 32nd place on the medal table with no gold medals to finishing 4th winning 16. In a similar fashion Great Britain, via funding from the National Lottery went from one gold medal (15 total) to 11 golds (28 total) between 1996 and 2000, with continued increases in funding from £88million in 2004 to £355 for Rio 2016 Games, culminating in 29 gold (65 total) medals in London 2012 Olympic Games and 27 gold (67 total) in Rio 2016 Olympic Games, a first for a nation to achieve more medals at the end of the cycle following a home Games (Independent, 2016).

To enable success at elite senior level, a steady stream of athletes capable of progressing to that level must be maintained (Vaeyens *et al.,* 2009). Sport talent programmes aim to systematically identify and develop talented athletes so that the best resources and funding can be directed to make the most impact (Abernathy, 2008), such as higher level coaching, equipment and access to facilities and support services (Vaeyens *et al.,* 2009).

Traditional talent programmes have not displayed a high predictive ability of elite Junior and youth athletes reaching the elite senior level in a range of sports including Australian football (Robertson *et al.,* 2014), cycling (Schumacher *et al.,* 2006), rugby league (Till *et al.,* 2014), gymnastics (Pion *et al.,* 2016) and football (LeGall *et al.,* 2010; Ostojic *et al.,* 2014) revealing a successful percentage of progression of between 6 and 35%. In an attempt to increase the accuracy of predicting progression talent programmes have sought to identify what the key characteristics are of athletes who have the potential to progress into elite senior sport and ultimately be successful on the highest stage (Abbott and Collins, 2002). A number of characteristics have been investigated to gain a greater understanding of developing elites including psychological factors, technical skills and multi-disciplinary batteries (Gould *et al.*, 2002; Greenleaf *et al.,* 2001; Pion *et al.,* 2016; Reilly *et al.,* 2000; Wiseman *et al.,* 2010; Woods *et al.,* 2016; Van Yperen, 2009) however this study will focus on the physical and anthropometrical factors.

The addition of physical characteristics aims to provide an objective set of data to compliment and add to the subjective assessment of playing ability from coaches (Abbott *et al.,* 2002) leading to a more focused support plan to optimise development (Bompa and Haff, 2009). The impact of adding physical characteristics is varied in predicting future elite progression across different sports (Lidor *et al.,* 2009), with a number of possible conflicting factors such as maturation status, differences in individual development rates, the use of age-inappropriate measures and the later emergence of skills and attributes in different athletes (Suppiah *et al.,* 2015; Vaeyens *et al.,* 2008). It is important to note that the interactions of physical characteristics and prediction of future elite status does not automatically imply that these factors are essential, these characteristics develop at different rates and individual athletes follow varied patterns of trajectories across a number of impacting attributes, also while considering that strengths in one area may compensate for weaknesses in another (Williams and Ericsson, 2005).

Due to the difficulty in predicting future elite success there has been a shift towards focusing resources on providing the best environment and opportunities to progress (Abbott *et al.,* 2002; Abbott and Collins, 2004; Martindale *et al.,* 2005; Vaeyens *et al.,* 2008). Embracing the holistic, multi-disciplinary individual non-linear trajectory of physical development (Bergeron *et al.,* 2015; Gulbin *et al.,* 2013). During the Junior and Youth stages physical characteristics have been shown to distinguish between elite and non-elite athletes (Lidor *et al.,* 2009; Pearson *et al.,* 2006), adding more information to the picture of development at different stages of development (Lawton *et al.,* 2012; Matthys *et al.,* 2013b; Mohammed *et al.,* 2009). Although it should be noted that a number of studies found no difference (Elferink-Gemser *et al.,* 2004; Franks *et al.,* 1999) and others reported distinguishing characteristics varying at different stages (Till *et al.,* 2013a; Vaeyens *et al.,* 2006). It is important that athletes are not purely assessed on one-off snap shots of performance and are profiled longitudinally relative to maturation status while considering the potential variation in performance throughout adolescent development (Vaeyens *et al.,* 2008). The longitudinal tracking of athlete's physical characteristics relative to future elite success may enable talent programmes to identify athletes who are on trajectory (Allen *et al.,* 2014; Lawton *et al.,* 2012; Vaeyens *et al.,* 2008). This would therefore aid the talent programme to direct support and resources to maximise an athlete's potential based on their individual needs (Allen *et al.,* 2014).

Physical characteristics have been shown to be crucial to elite athletes as competence in Fundamental movement skills provides athletes with the key foundations to developing complex sports-specific skills (Abbott *et al.,* 2002; Gagné, 2004; Jess and Collins, 2003). Lloyd *et al.* (2015a) devised a physical model of development (Youth Physical Development model where critical steps of fundamental movement skills are progressed onto generalised physical characteristics of balance, co-ordination, strength, agility, power and aerobic endurance. Development in these areas were endorsed for preparation for future elite athletes in the recent International Olympic Committee (IOC) consensus statement in youth athletic development (Bergeron *et al.,* 2015). Enhanced physical characteristics have been shown to reduce the risk of acute and overuse injury (Lauersen *et al.,* 2014) and have been linked to improving the effectiveness of hours of practice and skill development (Elferink-Gemser *et al.,* 2010; Kliegl *et al.,* 1989) both of which improve the quality of practice which is understood to be critical in elite sport development (Rees *et al.,* 2016; Tucker and Collins, 2012). Competence in physical characteristics can increase self-esteem and motivation leading to enhanced well-being and sporting participation (Lloyd *et al.,* 2015a). Physical training has also been shown to decrease the risk of a range of health conditions such as obesity and cardiovascular disease (Faigenbaum *et al.,* 2013).

Elite sailing is a complex sport that requires the combination of many factors including decision-making, cognitive function, tactics and a large technical component both in terms of boat design and physical skills (Bojsen-Möller *et al.*, 2007; Sjøgaard *et al.,* 2015). In recent Olympic cycles there have been advances in race format and boat design that has made elite sailing a more competitive and physically demanding sport (Bojsen-Möller *et al.*, 2014). The events raced in the Olympic Games may change every four years, with the physiological and anthropometrical requirements differing (Bojsen-Möller *et al.*, 2007) further complicating the developmental trajectories of elite pathway sailors. During a regatta sailors compete in up to two to four races per day lasting between approximately 25 and 60 min depending on the class for around five to seven days depending on the regatta. The exact schedule and race durations are determined by the wind, with long delays on the water possible due to adjustments being needed to make the course fair for all.

The physical characteristics of elite sailing have been researched (for full review please see section 2.5), with the predominance taking place in hiking positions in the Laser and at senior level versus Youth or Junior. Less is known in other classes such as trapeeze or boardsailors, but it is understood that the physical and anthropometrical requirements are different across different disciplines and are not comparable (Bojsen-Möller *et al.*, 2014). A variety of anthropometrical sizes are observed in Olympic class sailing, mainly due to an attempt to maximise righting moment while keeping body mass within specific boundaries for different classes (Bojsen-Möller *et al.*, 2014). The physical requirements for righting moment are a function of body mass and height (combined for double-handed classes), but also the ability of the sailor to withstand the specific counter-balancing forces produced by the sail and boat to keep the vessel flat and therefore go faster (Mackie *et al.,* 1999). Elite Junior and Youth sailing has received little attention, with all studies focusing on hiking classes. Most studies have investigated physical indicators of performance using sailing-specific assessments (Callewaert *et al.,* 2014b; Tan *et al.,* 2006). Studies using the EUROFIT testing battery (Council of Europe, 1988) have produced data to enable comparison of Junior and Youth sailors against age-matched sporting and non-obese non-elite samples (Callewaert *et al.,* 2014b; Deforche *et al.,* 2003; Matthys *et al.,* 2013b; Vaeyens *et al.,* 2006).

To the author's knowledge, no attempt has been made in the Olympic sport of sailing to identify the characteristics of successful developing elites across all classes. Therefore it is the aim of this study by using semi-structured interview with elite pathway coaches and Podium-level elite sailors, to understand what the key characteristics of successful development are.

3.2 Methods

3.2.1 Participant selection criteria

For coaches' inclusion, they must have been coaching at an elite level within the BST's Olympic pathway for at least five years. It was the aim of this study to have a mixture of male and female coaches, and to be confident of capturing a sample representative of the different trajectories of sailors a range of coaches that had experience in coaching single-handed, double-handed and boardsailing classes were desired. Athletes must have been either a current or former Podium level sailor, to have achieved podium finishes in senior European and/or World championships and to have been ranked within the top three in the world via sailing's international federation (World Sailing) classification (World Sailing, n.d.). Parallel to the coaches, it was required that a combination of male and female sailors were represented across the range of sailing classes (single-handed, double-handed and boardsailing).

In total twelve coaches and fifteen sailors met the selection criteria, but not all were recruited as it was established between the study researchers that saturation was achieved, confirmed as interview content became repetitive so that more participants would not add value to the analysis. All participants were contacted for inclusion within the interviews, all were informed of the requirements of their involvement and any ethical considerations before being asked to participate. Approval for the study was granted by the University of Chichester Research Ethics Committee.

3.2.2 Participants

Nine elite coaches and eleven elite sailors were recruited that made the criteria for selection. The coaches (37.9 ± 9.8 years) had an average of 12.7 years of coaching experience at the elite pathway level (range five – 20 years), and comprised of seven males and two females across whom had experience in coaching single-handed (5 coaches), double-handed (5) and boardsailing (1) classes. The sailors (30.4 ± 5.0 years) were current (8 sailors) or ex-Podium level sailors (3) who had all held an ISAF world ranking within the top two in the world. Within the sample were five Olympic medallists and four World champions. In total the elite sailors sample comprised five female and six male sailors who had competed in single-handed (4), double-handed (8) and boardsailing (1) classes participated in the interviews. All elite sailors included within this study were a product of the Olympic pathway, which was representative of recent Podium level success as an analysis of the 26 top two-World ranked sailors competing since 2004, including 16 Olympic medallists and 25 World Championship medallists, revealed 96% participated in elite Youth squads.

3.2.3 Procedures

Preparation for interview technique involved reading qualitative research (e.g. Côté *et al.,* 2005) and consulting with two appropriately experienced psychologists within the BST and the University of Chichester. The interviewer had been working with the BST for two years at the time of the interviews and had been involved in sport as a competitor and coach. Consequently the interviewer was familiar with sailing-specific terminology and could identify with experiences of sailors and coaches which aided in the building of rapport.

All participants were sent an email detailing the procedures and outlining the interview guide, prior to scheduling interviews consent forms must have been signed and returned. Due to the international nature of the sport, a range of locations and the preferred interview method were obtained with the participants where the interview could be completed in a quiet and confidential setting, finally a location and time was decided. For quality, Interviews were conducted face-to-face where possible, though due to athletes/coaches having busy schedules Skype video calls, or telephone calls were used, though due to the familiarity of the interview with the participants these alternate methods were deemed acceptable. Initial interviews lasted from 55 to 80 minutes in duration (mean duration 67 min). Follow-up interviews were also conducted, lasting 15 to 30 minutes (mean duration 21 min).

Participants were sent out the initial analysis from their group (coach/athlete) before the follow-up interview via email, the follow-ups were completed face-to-face or over telephone. Follow-up interviews were only possible with coaches due to time constraints of athletes. All interviews were digitally recorded and transcribed verbatim

3.2.3.1 Interview Guides

A semi-structured format was used for all interviews. The same set of questions were asked to all participants, however the delivery and timing of these varied to allow for the different flow of discussions between interviewer and participant. Prior to commencement of the first interview, rules based on the number and style of prompts were standardised to ensure consistency in line with the recommendations of Patton (2002). A limit of two prompts were allowed within each question across all interviews though this did not limit the flow of dialogue through the interview. The interview guide was critiqued by the same two experienced psychologists involved in training the interviewer on technique, to ensure the guide was clear and appropriate.

The interviews commenced with an ice-breaker question to build rapport and make the participant feel at ease (e.g. what was your finest moment in sailing?). Following the ice-breaker, the participants were reminded of the outline of the interview and assured that any discussions within the interview would remain confidential and their identity would be kept anonymous throughout the analysis and reporting of research findings.

The interview guide consisted of three sections: The first section included the participant being asked about the key aspects of the boats that they sailed/coached (e.g. the type of boat (s) and the key movements/skills involved). In the second section, participants were asked about what they thought were the key characteristics of sailors being able to progress up the Olympic pathway successfully, defined by consistently being in the top three in the world). During the interview the interviewer made notes of the participant's key comments, in the final section participants were shown the notes that had been completed and were questioned as to whether they felt that what had been collected was comprehensive, and then asked if they would like to add any more information.

3.2.4 Data Analysis

Following all interviews, inductive content analysis was performed separately between coaches/athletes (Patton, 2002). This process organised the transcript into meaningful quotes which are paraphrased and sorted into raw data themes. Further commonality was established within the raw data themes and higher order themes are created. Finally once further commonality was not possible and data fitted into the established higher order themes, these themes were organised into general dimensions. Examples of how the data was analysed is presented below (Quote > Paraphrased > Raw Data Theme > 1st Order Theme > General Dimension):

"We weren't just inherently fast because we weren't the right size" > Not fast as wrong size > within ideal anthropometrical range > Anthropometry > Physical

"I wish I'd made a bit more of that now and just had a better physical base" > Building a better physical base > Conditioning > Components of fitness > Physical

The analysis followed the steps outlined below:

1. Transcripts were read by interviewer until fully accustomed with the data.
2. Analysis was completed by interviewer as per guidelines above.
3. A second independent qualitative researcher, a postgraduate psychology student from University of Chichester performed steps 1 and 2 above on all data.
4. Both interviewer and second qualitative researcher then met to discuss analysis until agreement was found in all coach and athlete interviews.
5. When the analysis was complete, a third researcher, or 'critical friend' (Faulkner and Sparkes, 1999) who was employed as a development sports psychologist with BST and was not involved in steps 1-4 was invited to sense-check each stage asking questions to clarify all points of disagreement. In the instance of disagreement, the

interviewer's comments were most valued as has had first-hand experience of the data collection.

6. Once complete, all themes and general dimension citations were summed to provide a hierarchical order.

3.2.4.1 Trustworthiness

The current study included methods to enhance the trustworthiness of the findings. This was evidenced by the following steps: Both the interviewer and third researcher had experience and knowledge in the sporting context of sailing and therefore were able to empathise during data collection and provide a second check on the quality of the process, the second researcher was experienced in qualitative research methods and therefore all stages of analysis were credible when triangulating the analysis (Patton, 2002). The coaches and athletes were able to view their initial thoughts and make further comments at the end of the initial interview giving them the chance to amend any omissions made. The coaches were sent out the summary and initial format of the content analysis, so that they were able to gain an overview of how their comments fit within the larger sample of their peers, and then these coaches were able to add/remove their original thoughts. Within the sample of coaches and athletes there were male and female participants, plus every genre of sailing class, making the content representative of the Olympic pathway. The selection criteria of athletes and coaches required all participants to be experienced in elite sailing, either coaching at the highest pathway level or being an athlete amongst the top 2 performers in their class in the world.

3.3 Results

3.3.1 Descriptive overview

A total of 312 pages of double-spaced data were obtained from all interviews conducted which yielded 1485 meaningful quotes which were extracted from the transcriptions of coaches and athletes. From these quotes emerged 78 raw data themes of key characteristics of successful development within the Olympic pathway. Eleven higher order themes were created comprising of: Components of fitness, On-water Physical, Anthropometry, Cognitive Function, Mental Processes, Psychological Characteristics, Purposeful development, Preparation to sail, Performance Lifestyle, Game plan and Development environment. Three general dimensions covered all themes from the interviews in both coaches and athletes, titled: Physical, Mental and Development. The output of the content analyses can be seen in Figure 3.1 and Figure 3.2.

Raw data themes	P	1st order themes	P	General dimensions	P
All-round fitness	8	Components of fitness	9	Physical	9
Conditioning	7				
Strength	7				
Aerobic fitness	7				
Agility	7				
Whole body effort	6				
Balance	5				
Injury free	4				
Co-ordination	4				
Power	3				
Flexibility	3				
Technique	9	On-water Physicality	9		
Boat speed	6				
Feel	5				
Responding to conditions	3				
Starting	3				
Within ideal anthropometrical range	5	Anthropometry	5		
Leverage	2				
Perceiving & Interpreting the environment	9	Cognitive Function	9	Mental	9
Decision-making	8				
Spatial Awareness	6				
Intelligence	5				
Pattern Recognition	3				
Reaction time	1				
Strategy & Tactics	8	Mental Processes	9		
Self-control	5				
Problem Solving	4				
Goal setting	2				
Hardworking attitude	6	Psychological Characteristics	8		
Communication	6				
Honesty	3				
Commitment	1				
Fun	1				
Learning	7	Purposeful development	9	Development	9
Understanding	7				
Purposeful training	6				
Sailor-driven	4				
Experience	3				
Becoming an athlete	2				
Parental Support	1				
Talent	1				
Boat set-up	6	Preparation to sail	9		
Routines	6				
Priorities	5				
Physical Preparation	3				
Nutrition	3				
Preparation	3				
Rules	1				
Managing transitions	8	Performance Lifestyle	9		
Performance Lifestyle	2				

Figure 3.1 Key characteristics of successful development through the Olympic pathway (coach analysis, n= 9) displayed in hierarchical order. Note: The darker shading represents greater participant acknowledgement within interviews, P – number of coaches that mentioned the theme

Raw data themes	P	1st order themes	P	General dimensions	P
All round fitness	8	Components of fitness	11	Physical	11
Strength	7				
Aerobic fitness	7				
Conditioning	6				
Injury and illness prevention	6				
Agility	4				
Co-ordination	2				
Balance	1				
Power	1				
Technique	11	On-water Physicality	11		
Boat speed	7				
Feel	6				
Starting	4				
Within ideal anthropometrical range	9	Anthropometry	8		
Leverage	2				
Drive	9	Psychological Characteristics	11	Mental	11
Hardworking attitude	9				
Desire success	6				
Competitive	6				
Confidence	5				
Mental toughness	4				
Natural ability	4				
Motivation	3				
Commitment	3				
Intelligence	3				
Methodical	2				
Honesty	2				
Mature	2				
Ruthlessness	2				
Perceiving and Interpreting the environment	11	Cognitive Function	11		
Concentration	7				
Decision-making	7				
Spatial awareness	2				
Strategy & Tactics	10	Game plan	10		
On-water priorities	3				
Risk management	2				
Pain tolerance	4	Mental Processes	10		
Imagery	3				
Performing under pressure	3				
Self-control	2				
Goal setting	2				
Volume of sailing	8	Purposeful development	11	Development	11
Sailor-driven	8				
Purposeful training	7				
Experience	6				
Understanding sailing theory	6				
Independent learning	5				
Learning	5				
Fun	11	Development environment	11		
Participation in other sports	9				
Parental Support	8				
Balancing non-sailing commitments	4				
Support structure	4				
Finance	3				
Proximity to sailing venue	2				
Physical preparation	8	Preparation to sail	10		
Boat set-up	7				
Preparation	7				
Communication	5				
Nutrition	3				
Routines	2				
Hydration	1				

Figure 3.2 Key characteristics of successful development through the Olympic pathway (athlete analysis, n = 11) displayed in hierarchical order. Note: The darker shading represents greater participant acknowledgement within interviews, P – number of athletes that mentioned the theme

During content analyses, the total number of participants that acknowledged raw data themes, higher order themes and general dimensions can be found in Figure 3.1 and Figure 3.2. It is clear from the content analyses that sailing in the Olympic pathway is a complex multi-dimensional sport that requires a large amount of characteristics and abilities to be successful, in accordance with the editorial published for the European College of Sports Science 'Science in sailing' symposium (Sjøgaard *et al.,* 2015). The general dimensions of Mental and Development comprise many areas that warrant further understanding and research, however the focus of this thesis comprises of the physical and physiological aspects of successful development through the Olympic pathway. Therefore the Physical general dimension will be explored further (see Figure 3.1 and Figure 3.2).

3.3.1.1 Coach and athlete analysis

Within the coach interviews the Physical general dimension comprised of 18 raw data themes organised into three higher order themes: Components of fitness, On-water Physical and Anthropometry. All nine coaches that were interviewed included themes within the Physical general dimension. Within the athlete interviews the Physical general dimension comprised of 16 raw data themes organised into three higher order themes: Components of fitness, On-water Physicality and Anthropometry. All eleven athletes that were interviewed included themes within the Physical general dimension.

3.3.2 Further analysis

This section will investigate the content analysis in further detail, initially splitting into higher order themes (On-water Physicality, Components of Fitness and Anthropometry) and individual raw data themes. Findings from both coach and athlete analyses were compared against each other, with the aim of first identifying commonality and then differences between the two groups in each section.

3.3.3 On-Water Physicality

Raw data themes within the 1st order theme of On-Water Physicality comprised of physical aspects of sailing that sat outside of components of fitness that can be profiled on-land, including: Technique, Boat speed, Feel, Responding to conditions and Starting. Where themes in this section relied on non-physical characteristics, these were positioned elsewhere in the analysis, to use an example: Boat speed is heavily dependent on physically propelling the boat forwards, however in double-handed classes communication is key to making adjustments to the boat in the water, for example: *"How they talk to each other in the boat is essential, so communication, that is a huge thing because you can't make any change to the way the boat is sailing without both of you making the change"* therefore to maintain consistency in analysis 'Communication' was placed in 'Psychological characteristics' within the 'Mental' general dimension.

It is clear from the analysis that all coaches and athletes referred to themes within 'On-Water Physicality' during the interview process, that on-water physical characteristics specific to sailing are important to being successful in Olympic sailing. However it was decided that further analysis of these themes was outside of the scope of this thesis due to the complexity and randomness of the on-water environment, and the time resource required for fully understanding the class and position-specific range of themes/movements. The process of profiling on-water physical characteristics for approximately 300 pathway sailors twice per year as part of the squad-based programme would be impractical due to the external factors or 'uncontrollables' that are evident with on-water measurement and racing, and the thirty possible sailing positions to analyse across the Olympic pathway please see Figure 3.3. The aim of this chapter is to confirm key physical characteristics that can be profiled in a controlled setting to reduce variability so that the programme/coaches/sailors can be confident of the process.

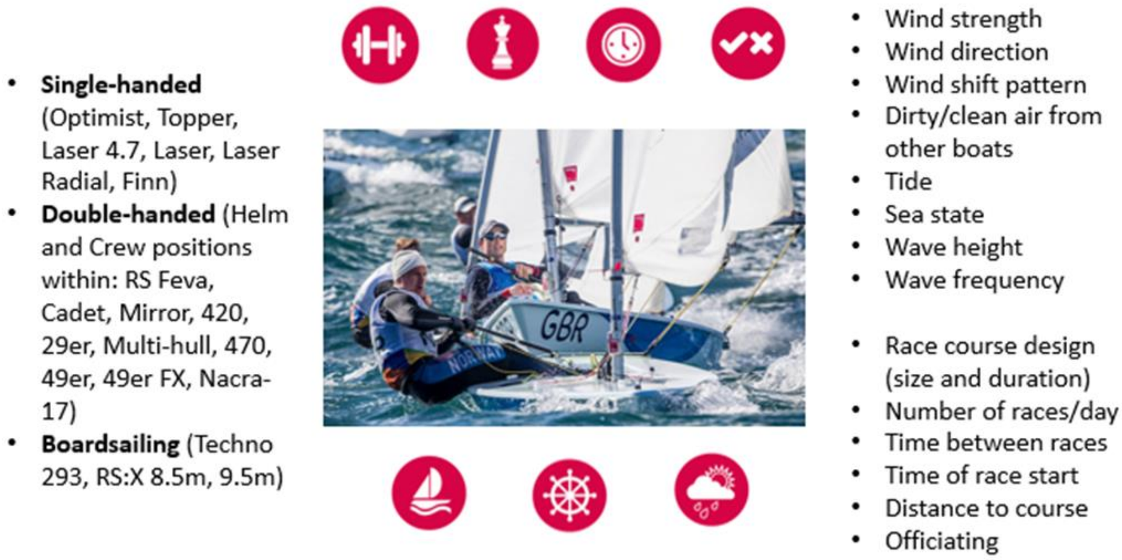

Figure 3.3 Possible number of sailing positions and uncontrollables for on-water measurement and racing

3.3.4 Components of Fitness

Nine common raw data themes emerged from this higher order themes between groups: All-round fitness, Strength, Aerobic fitness, Conditioning, Agility, Injury free, Balance, Co-ordination and Power. The coach group added Whole body effort and Flexibility to comprise eleven raw data themes in total. Components of fitness was mentioned by all participants within both sets of interviews, emphasising the importance of physical fitness within the Olympic sailing pathway. Themes are ordered by the total number of participants that commented on the theme:

3.3.4.1 All-round fitness

All-round fitness content comprised of comments relating to all-round athleticism or where multiple components of fitness interact together. At the most basic level both coaches and athletes included phrases such as "*fitness*" within a list of important characteristics or "*there is a need for all-round fitness*". There was commonality in the importance of having a decent level of all-round fitness at a younger age: "*Just to have basic level fitness for me that just sits at the base i.e. that they can just run around and have just general good fitness*" or "*Having that good base when you're younger*".

When compared to higher levels within the pathway, "fitness becomes non-negotiable" and "in the Juniors where a general level of fitness would get you by, that is suddenly not the case anymore". It appears as the performance level increases the demand for all-round fitness increases and results in producing a performance impact; athletes commented that "*my limiting factor was my physiology*" and "*I just wasn't fit enough*", coaches are in agreement and one put it succinctly as:

"The underlying message is the fitter and faster the sailor is, the better they'll learn and the better they will perform, It is important for sailors to realise that fitness is free speed around the course"

These jumps in physical requirements are evidenced around transitions, from Junior to Youth *"It is much easier to get away with it at the Junior level to a certain extent with just reasonable fitness that you will not get away with it in* Youth *classes, no chance" or* where athletes move into the adult Olympic classes: *"[The] 49er is a big step up as it becomes a big platform they need to run around on, a big unstable slidey platform - so the most important stuff is around the agility and strength"* or *"I see that in the younger guys coming through, they don't have a general fitness, a good enough base. So they'll try and do what we're doing, so we're sailing in the morning or whatever and do quite a hard session, and then they're knackered for the rest of the day. So while we'll do another session in the afternoon and they try and keep up with us, and they get ill or injured or whatever, or they can't do it, so they don't".*

Two athletes put all-round fitness into perspective by saying "*I don't think you necessarily need to be really fit to be good, but being fit doesn't hold you back*", and "*I'm not convinced about the need to excel [in fitness], I think the demands of Olympic sailing are that you need to be fit, we're not talking about creating a rower - some of the boats in the Olympics don't even require you to be fit, like the 49er helm or the 470 helm, you don't even need to fit. Boats like the Finn you do".* This highlights that different sailing classes/positions in the boat require different levels of all-round fitness, or that it is not comprehensively viewed as the most critical factor for success in sailing.

3.3.4.2 Strength

The raw data theme of Strength included comments relating to overall strength and specific areas of the body that need to be strong for sailing. Both coaches and athletes mentioned the term *"strength"* when listing key characteristics or similar quotes highlighting the importance of strength such as *"the muscular side of things", "strength: weight ratio"* or simply just *"being strong"*. One of the athletes commented on the physical state of youth sailors *"individuals vary so much at that age as well, in terms of you get some that are just* *so scrawny and no strength at all that I think anything they could do strength wise would probably be a bonus!"*

Commonality existed in the majority of interviewees in the importance of strength, especially when related to *"specific strength"* during sailing movements and the corresponding muscle groups. The most mentioned movement related to strength was in *"hiking muscles"* – a number of coaches and athletes referred to the same muscle groups in different orders of importance, for example: *"In terms of the muscles that need to be strong it is mainly the quads, hip flexors and core. Probably in that order depending on different styles"*, *"When it comes to hiking, being strong in your core probably comes first … next comes legs and then lower back comes in"*, "*the key strength area is in those core muscles of the stomach, and their legs".* Core strength appears across a number of classes, not just in hiking as in boardsailing *"When it comes to manoeuvres the most important thing is core strength"* and also *"For the crews it can be really physical because they've got the unlimited pumping rule above certain wind strength and so upwind they are body pumping/flicking on the wire [trapeezing] which just destroys your stomach muscles".* Upper body strength is also mentioned across both groups such as: *"using your upper body strength to play the main sheet", "The first thing that they generally have trouble with is their grip strength"* or *"you would actually be surprised how much work the chest does, but that is probably when the core gets knackered".*

Similar to increases in all-round fitness when transitioning to Olympic classes, coaches mention the increased strength requirements *"So the forces all change really really quickly, and they may be strong, but suddenly they are not in control the boat", "As they work up the ladder the physical side becomes more and more important".* This is also evident in training as *"There is a greater amount of strength that they need to just sail the equipment and move the rig around"*, more specifically linked to strength aiding the ability to learn when sailing a class that creates greater loads *"Improve their strength which would help their technical progression".*

On the other end of the spectrum, one athlete was quoted as saying: *"I never felt a huge need for leg strength and so, yeah [I] didn't do much."* Supporting the earlier thoughts on the range of all-round fitness requirements in the different classes/positions in the boat.

3.3.4.3 Aerobic fitness

It may be possible from reading this section without the context of the transcripts that there is overlap regarding 'fitness' as some interviewees have used the term interchangeably to relate to different raw data themes within the physical dimension. The differentiation between All-round fitness and aerobic fitness in this analysis resulted from either the specific mention of *"aerobic fitness"*, "*high aerobic fitness"* or *"good aerobic base"* or the interaction of the aerobic nature of fitness. The need for aerobic fitness is consistent across both groups of interviewees similar to All-round fitness, one athlete mentioned that it would be *"hard to look past the aerobic side".*

Coaches and athletes referred to the benefits of aerobic fitness to support training and in the acquisition of skill, with comments such as; *"The key is the fitness element … they can be out for longer on the water which means it increases the amount of time they can learn new techniques in the changing environment"* or simply put *"having enough aerobic fitness to be able to do the hours on the water".* Performance benefits of possessing greater aerobic fitness were also common between both groups in the ability to maintain technique, for example; *"a successful laser sailor will use the upper body kinetics to transfer power through your lower body into the boat and work rate and heart rate reaches near maximum, and that is where the less fit people struggle because they haven't aerobically got the ability to go and do that".* In the boardsailing classes particularly, fitness plays a large role in performance; "*being quick is related to board handling, pumping technique and fitness. Once you have the speed you can make everything easier, for example if you have a bad start, but you're quick you can get yourself out that problem".*

The majority of interviewees linked greater aerobic fitness with the ability to maintain performance over the course of a regatta; *"The key is to be aerobically fit – you need the low-end fitness that gets you through regattas, between races, as well as having the top end to be able to perform three races a day" or "There is an endurance part, whether it is in a single race or day after day after day, if it is a five-day regatta to be successful we will need to have people that when they get to that last race they are as capable at that stage than at the beginning of the week".* One coach went into more detail about one specific sailor:

"One of our transitioning sailors is probably strong enough but lacks the aerobic fitness, he might be fit enough to do one race but not three in a row. In his first Olympic level regatta

I thought his fitness was pretty good, but as the races went on he was starting to struggle on the last couple of legs due to fatigue from the bigger sail. So fitness again is the key factor"

Coaches and athletes referred to the link between having a good level of aerobic fitness and preserving cognitive function on the water: "*The physical demands can overtake what they're thinking, so the fitter the person is, the more brain space there will have left to make the decisions*", "*an important point is having mental robustness even through the physical demands of sailing the boat*" and especially in the single-handed Laser class: "*in the laser you need to be able to grunt it out for hours on end and still be able to mentally think your way around the racecourse*". Athletes supported these comments "*if you have a really good fitness level, you put your concentration into a more important area*", "*the fitter you are, the easier it is to make decisions*" and "*it gives you the ability to sail the boat better for longer because obviously the better you are at doing the physical work, then the less concentration you use*".

3.3.4.4 Conditioning

The raw data theme of Conditioning relates to the ability to sustain strength over long durations, including the resistance to muscular fatigue and the physical requirement in the maintenance of posture in the boat/on the board. Both groups of interviewees mentioned conditioning-related quotes without further explanation of within lists of key factors such as; *"core conditioning", "general level of conditioning", "good overall conditioning"* or *"it is muscular endurance, it's being able to sustain".*

Commonality existed in both groups with references to the requirement of good conditioning for maintaining technique for performance benefits across a range of sailing classes; *"People will start blowing up and their technique gets shit or they stop pumping or whatever, because they're just knackered"*, *"if you can pump the rig for longer you will generally go faster"* or *"so the more main sheet they can move, the faster it will go especially when it's windy, so it pays to have a bit of upper body endurance".* Added to the importance of conditioning for technique was the impact of the environment - *"When it gets windier, the loads on your ropes get higher"* placing a greater strain on muscular endurance, one athlete went as far to say; *"you could almost attend an event and almost pick who was going to do well depending on the wind strength and it was all down to the physical capability".*

Coaches and athletes highlighted the importance of conditioning around the key transition point between Youth and Olympic class sailing as for example, poor conditioning can limit the ability to use decision-making on the water; *"everybody suddenly becomes well-conditioned, and everybody's techniques are at such a level that it's very hard to start using your decision-making as you're trapped in between boats and there is no space".* One coach noted that; *"the overall conditioning and core work is making a massive change to the* Youth *guys coming through".* One particular athlete reflected on their physical development around this transition saying; *"If I look back on it now it was such an easy gain it would have been the obvious thing to do … I guess I wish I'd made a bit more of that now and just had a better of a better base".*

3.3.4.5 Agility

Agility was categorised as a theme through the need for quick, accurate movements while sailing or the general ability to move efficiently. Coaches and athletes both mentioned the need for being agile, referred to within interviews as simply the importance of *"agility"* or *"good movement skills"* in successful sailors.

Good movement quality was expressed repeatedly by coaches and athletes as being *"cat-like",* for example; *"Having that catlike ability or gymnastic ability in both crew and helm builds a strong and agile boat. The [speed] difference between a smooth versus a clunky boat can be massive, if you were to have some kind of vibration sensor you would see huge differences and that can be massive in the sport. Smooth almost artistic movements in the way the continental sailors generally move, almost like they are painting a picture like Pablo Picasso versus just bumping along the side of the boat."* According to both groups agility related to superior performance on the water, not just limited to a particular stage of the Olympic pathway, as the need for agility is displayed at both Youth - *"With the boats going faster, they need to go faster so their response time needs to improve, it should be fast already in a Junior boat, but it is now highly critical as one of them, the crew, could be completely out of the boat and in a moment needs to be inside the boat, under the boom and out the other side",* and Olympic level - *"I think agility is a big deal. I've spent a lot of time in my later years now 470 sailing, spending a lot of time on kind of quick movement".*

Coaches typically went into more detail about how agility can improve particular manoeuvres or aspects of sailing: *"Downwind the boat becomes more unstable therefore agility becomes quite important"* or *"When you're gybing the sail moves really quickly,* *therefore you have to move quicker and you can get punished for it is a lot more if you don't move as quick as you should and can end up upside down and that's your race pretty much over".*

3.3.4.6 Injury free/Injury and illness prevention

Content within the raw data theme of injury free/injury and illness prevention related to the requirement of robustness in terms of being resistant to injury or illness, or reflections on their own careers as to how injury significantly affected their development/performance. Coaches and athletes both mentioned the importance of *"injury prevention"*, *"resilience to illness"* and to *"be robust and injury free"* as statements within lists of key characteristics, one athlete put succinctly; *"A big one is injury prevention - a big one".*

Coaches and athletes identified prone areas to injury; *"I think not being injury-prone is key. I mean, some people have a lot of problems with their backs. I don't. It gets stiff and it gets sore … I think you've got to have good arms and a good back and you'll be fine"* or *"I've had a few back issues and knee issues and feet issues".* Both groups mentioned the need for preventing injuries earlier in the Olympic pathway relating to technique - *"It tends to be the reason that lots of sailors end their sailing and end up coaching, the overuse injuries of particularly the knees makes me particularly concerned of making sure the Juniors' hiking positions are good. So making sure their legs are straight, focusing on the right muscles, making sure knee- hip alignment stays true. It's really important that we don't injure them at such a young age"* and muscle imbalances; *"the down side of that [increased sailing volume] was injury from that 'cos you know that if you only do one thing you become quite imbalanced … I had knee problems when I was a kid, growing up and from hiking the boat, the Topper particularly with a bad hiking position."*

Athletes in particular related the need for injury prevention from their own personal careers, where in one case it cut their Olympic campaigning short and detracted from their training - *"What I really needed to be told was the injury prevention side of things, which for me was a big problem in my career. My biggest regret is that with injuries I stopped my career earlier than I'd have liked to and felt like I would have spent less time in the last few years with dealing with injuries."*

3.3.4.7 Balance

Balance was highlighted as important in both coach and athlete interviews, solely quoted as *"balance"* within lists of key characteristics, however when analysed separately coaches related balance to the performance of specific manoeuvres for example; *"gybing which requires quicker movements across the boat, combined with balance and proprioception as it is more risky manoeuvre with a greater chance of capsize"* and "*When going downwind there is a balance element, you are trying to sail the boat smoothly on an unstable surface because that is quicker the key thing is the interaction between body weight in the seated position, the way you steer the boat over the waves judging what is about to happen next with regards to is going to cause instability and therefore what movements are required to counteract it*" and *"balance in moving, stepping in and out, nothing is happening really fast, but you have to be really smooth with your movements".* Athletes spoke more generally about balance such as; *"It is more about balancing the force of the rig, so it is more a whole-body thing rather than say balancing on a Swiss ball, so it is more balancing how much you lean back in relation to the amount of force in the sail"* and how it affects the mental side of sailing *"balance would allow me to sail the boat on autopilot, so I could spend more time concentrating".*

3.3.4.8 Co-ordination

Co-ordination content related to the requirement of co-ordinated movement or manual dexterity. Both coaches and athletes cited co-ordination as important to sailing success, either by listing *"co-ordination"* or *"hand–eye co-ordination"* as part of a list of key factors or through explanation of manoeuvres or general skills on the water. An athlete and coach termed it simply as *"knowing where your hands and feet are"* or *"I would say co-ordination is also important … as you have to move your arms and legs in unison with what you are trying to do with the boat i.e. steering it."*

On-water examples that coaches and athletes used included the following*: "generally sitting with head over their knees and knees over their feet in the boat, and they need to go from a sitting position to effectively a standing position whilst their hands are busy doing other things, whilst travelling at 10 to 12 miles an hour and steering the boat"* or *"You have gybing where the back of the boat turns through the wind when going in the same direction as the wind that is a much quicker movement which requires more co-ordination".*

3.3.4.9 Power

Power, and specifically *"power to weight ratio"* was mentioned by both groups of interviewees and relates to the ability of the sailor to produce powerful movements on the water. Specific key areas of racing were mentioned in particular, for example; *"The power to explode off a start line pumping as fast as you can and depending on conditions, there may be other points in the race where you need that power to get the board moving as fast as possible"*, *"It requires a degree of explosivity at times when sheeting in around the bottom mark or at start time, jumping out of tacks in and out of the toe straps"* or during manoeuvres; *"the boat is really twitchy when going through manoeuvres. Especially for the crew being able to go fast from lying out flat on the wire and then power up through that into a half squat in the middle and then jumping out again".*

Other mentions centred on core skills; *"As long as you've got a good power to weight [ratio]"*. One coach highlighted the increase in the requirement for power in athletes when transitioning from Youth to Olympic class sailing - *"There's probably more of it that surrounds powerful fast movements, as in all the movements you are reaching out and going on as fast as possible as the quicker they can turn the boats the better the manoeuvre is. You could say it is about building the speed in the 29er and then adding power and the force in the 49er".*

3.3.4.10 Whole body effort

The separation of physical effort from the key physical characteristics was only highlighted by the coaches. This is categorised by the specific mention of effort on top of the physical characteristics that have already been recorded in this results section. Coaches made particular reference to the performance benefit on the water of increased effort; *"They go faster, just from putting more effort into their boat, for me you know sometimes it is just a work hard day. The harder you work the faster you go. Generally it is these people that perform better"* this was specifically important in tougher conditions - *"you are rewarded by the effort that is put in as it gets windier – so the harder you work the windier it is, the faster you will go".* When moving up to Olympic class sailing there are numerous factors that require athletes transitioning to put in more effort: *"There is less opportunity to be able to have gaps in your game basically and the races are harder in more difficult venues with stronger winds and tougher conditions, you have to work harder because you're against a better fleet"*

3.3.4.11 Flexibility

Flexibility was only mentioned by coaches within the interviews, as purely *"flexibility"* or *"they [athletes] need to be flexible"* or how it affects efficient movement on the water: *"Through those specific manoeuvres there is a degree of flexibility that is required in order to cross the boat in the fastest and least obstructive way".* Flexibility, particularly in lighter wind sailing becomes more important as it impacts upon technique and ultimately performance: *"In the light winds you have to be able to put your body into all kinds of different positions, this makes you more effective at getting your weight transferred through the hull – this needs to be subtle without disrupting the flow of the boat - you can't be an elephant, you have to be light-footed, dynamic and to be able to bend, stretch and twist. Within these movements they also have to be able to use their body as a lever, transmitting force through their toe straps, bum and legs. So they need to be flexible", "The movements go through a whole range, so you have the static strong movements while hiking upwind, but as you have the tacks and gybes to change the boat's direction for those you need to be able to bend and flex"*

3.3.5 Anthropometry

Two common raw data themes emerged from this higher order themes between groups: Within ideal anthropometrical range and Leverage. Anthropometry is critical in sailing, as the effect that body mass and height combined have on counterbalancing the force of the wind through the sail and on the vessel's displacement in the water has profound impact on speed. The range of sailing classes that are competed in at Olympic level differ greatly in terms of individuals' required anthropometric characteristics (Bojsen-Möller *et al.,* 2014) see Figure 2.13.

3.3.5.1 Within ideal anthropometrical range

Coaches and athletes both cited being within the correct anthropometrical range as important to being successful in sailing. The relative importance of body size becomes greater as athletes progress up the Olympic pathway as described by one coach:

"The whole way through this process from Junior to Youth *to Olympic there have been rough brackets of heights and weights and to how fit they should be, but as soon as you get to Olympic racing it is non-negotiable – if you are not tall and fit you won't win races. So the levels below are about developing traits and the top level is about sculpting athletes. During their development you also don't know exactly what size or shape they're going to finish at*

… if they are off those lines then the barrier for getting to Olympic level in the laser is that they are just not going to be the right shape. This means they have to go and do something else, for example double handed sailing or you just stop, you just can't get around it - if you're not tall enough or too big or small you won't make it. You have sailors that are really short that do well and about 50% of regattas and then really averagely in the other half, so you need to be good in all conditions and exceptional in a couple."

Athletes are in agreement: *"All the way through it gets more important and being able to be the right size for your boat, fighting a boat is too hard. If you want to scrape gold fleet which is what I did in a Radial, then yeah you can be the wrong size, but I think you've probably got a limit on how far you can go."*, *"Every boat requires different heights and weights. I think it's important to choose a class that suits you, that you are the right size for. I know many people that I've raced against that have failed, and part of their failure is their physique", "Being realistic about your height and weight is a big deal. The amount of people you see today in Olympic classes that are the wrong size, I could tell you now they're not the ones that stand on the podium. They might do now and then, but they certainly aren't going to the Games and standing on a podium."*

One athlete commented on their own progression and how anthropometry affected performance directly: *"We weren't just inherently fast because we weren't the right size"*

3.3.5.2 Leverage

The previous quote links Leverage to anthropometry, as the two themes are closely related. In the interviews both coaches and athletes highlighted leverage in particular as a key characteristic, the two themes are different however as leverage is a result of anthropometry plus the ability to harness it to a speed advantage: *"Obviously leverage, the faster you go"* or *"The more leverage the better especially when the breeze is up".*

Athletes referred to the added leverage as a performance advantage against other competitors, and how it can supersede other physical characteristics: *"Because everyone's fitness is fairly high you start to notice some of the physical differences. So you have someone who is 6ft 2 and someone who's 5ft 8 racing against each other, no matter how fit the short of person is they're always going to be giving away leverage which turns into boat speed" or "I'd like to be taller, for more leverage, but that's kind of scary being a small person, a short person, because if there was someone that was the same as me in every* *other way apart from they were taller, then they definitely would be better. Well they could make a boat go faster".*

3.4 Discussion

The aims set out for this chapter were to identify key physical characteristics of successful development in elite sailing. Key characteristics were obtained via semi-structured interviews with nine elite pathway coaches and eleven top level senior elite Podium level sailors (all ranked in top 2 in the world, including multiple Olympians). The 1st order themes including components of fitness and anthropometry were analysed from just under 1,485 individual quotes containing the following raw data themes: Components of fitness; Strength, Conditioning, Aerobic fitness, Agility, Balance, Co-ordination, Power, Flexibility, Whole body effort, Injury free and All-round fitness, Anthropometry; Within anthropometrical range, Leverage. It must be noted that other themes were produced from the analysis including on-water physicality, plus the Mental and Development general dimensions however this study purely focuses on the physical general dimension and more specifically the components of fitness and anthropometrical characteristics.

Commonality was observed across the majority of physical characteristics, revealing a high level of agreement between elite pathway coaches and elite athletes when considering the key characteristics of successful elite sailor development. However, there were potential differences in the relative importance of physical characteristics placed against the other general dimensions of Mental and Development, a few quotes from the athletes corroborate this finding: one athlete said "*I don't think you necessarily need to be really fit to be good, but being fit doesn't hold you back*" another mentioned *"I never felt a huge need for leg strength and so, yeah [I] didn't do much."* Potentially putting the impact of fitness in context against other characteristics, or potentially revealing the different physical requirements of different Olympic classes.

The elite coach analysis added two extra raw data themes of Flexibility and Whole body effort. Flexibility was added due to the extra specific physical nature of being able to "*bend and flex"* during key upwind and downwind manoeuvres. This may possibly be from viewing the characteristics from a more detailed coach's eye versus the retrospective recollection from the elite athletes. The extra mention of Whole body effort from the elite coaches may come from the recent need to promote hard work and effort for encouraging successful developmental behaviours in sailors they coach, but also the concept of rosy recollection from the athletes where events are looked upon more favourably after time has passed (Mitchell and Thompson, 1994). Within the Anthropometry 1st order theme only five out of 9 elite coaches versus 9 out of 11 elite athletes mentioned being within anthropometrical range as a key characteristic of successful elite development, this may be due to the relative importance of body size during the pathway up to senior elite sailing, one athlete confirmed this finding by stating *"Being realistic about your height and weight is a big deal. The amount of people you see today in Olympic classes that are the wrong size, I could tell you now they're not the ones that stand on the podium. They might do now and then, but they certainly aren't going to the Games and standing on a podium."*

The following section identifies the raw data themes and the link with previous research in physical characteristics within elite sailing and athlete development:

The importance of Strength for sailors at all stages of development and in all groups has been observed, particular in more sailing-specific muscles as knee extension strength has been shown to differentiate between performance level in senior and Junior hikers (Aagaard *et al.,* 1998; Burnett *et al.,* 2012; Tan *et al.,* 2006; Vangelakoudi *et al.,* 2007) with female sailors exhibiting similar strength to a group of male controls (Aagaard *et al.,* 1998). Other muscles groups such as the trunk (Niinimaa *et al.,* 1977), forearms (Callewaert *et al.,* 2014b; Niinimaa *et al.,* 1977;) and upper and lower body musculature have been stated to be key in sailing at elite senior sailing across all groups (Allen and DeJong, 2014; Buchanan *et al.,* 1996; Dyson *et al.,* 1996; Larsson *et al.,* 1996). The specific muscles used within sailing were highlighted in the interviews where elite coaches and athletes related to "*specific strength*" and "*hiking muscles*", specific to movements and techniques within respective groups, for example "*upper body strength to play the mainsheet*" though it is clear that strength in a range of muscle groups are key across different groups.

The ability to maintain the high level of force production over time is particularly evident in all elite groups in lower body (Aagaard *et al.,* 1998; Castagna and Brisswalter, 2007), trunk (Larsson *et al.,* 1996; Niinimaa *et al.,* 1977) and upper/whole body (Larsson *et al.,* 1996; Vogiatzis and DeVito, 2014), and also in Junior and Youth elite sailors (Callewaert *et al.,* 2014b, Tan *et al.,* 2006). This is reflected in the interviews as Conditioning linked to maintaining technique and performance where *"if you can pump the rig for longer you will generally go faster"* or in one case the importance of a high level of conditioning when the conditions become tougher: *"you could almost attend an event and almost pick who was* *going to do well depending on the wind strength and it was all down to the physical capability".*

Aerobic Fitness was highlighted as a key requirement across all groups at elite level with hikers' aerobic fitness being compared to team sport players (Bojsen-Möller *et al.*, 2007) and board sailors being compared to Olympic rowers (Vogiatzis and DeVito, 2014). The level of aerobic fitness in elite Junior and Youth sailors is also highlighted as Juniors were recorded to have relative $\dot{V}O_{2max}$ values similar to elite senior hikers (Callewaert *et al.,* 2014a) and differentiated between elite and non-elite levels in Youth sailors (Callewaert *et al.,* 2014b). The higher aerobic demands of boardsailing are reflected in the interviews and the key impact to performance as "*being quick is related to board handling, pumping technique and fitness. Once you have the speed you can make everything easier, for example if you have a bad start, but you're quick you can get yourself out that problem".* High levels of aerobic fitness appear to help maintain performance as *"The key is to be aerobically fit – you need the low-end fitness that gets you through regattas, between races, as well as having the top end to be able to perform three races a day".*

The less researched physical characteristics recognised as being key to elite sailing performance mentioned in the interviews such as Balance (Niinimaa *et al.,* 1977), Agility (Allen and DeJong, 2006; Bojsen-Möller *et al.*, 2007; Bojsen-Möller *et al.*, 2014) and Co-ordination (Callewaert *et al.,* 2014b) are evident through all stages of development. These physical characteristics are mentioned through either general "*good movement skills*" or through particular manoeuvres "*balancing the force of the rig***"** including a speed advantage as *"Having that catlike ability or gymnastic ability in both crew and helm builds a strong and agile boat. The [speed] difference between a smooth versus a clunky boat can be massive".* The importance of power was only highlighted in elite Youth sailors (Callewaert *et al.,* 2014b) as being comparable to similar aged football players (Vaeyens *et al.,* 2006), however power is mentioned at a number of moments on a race course "*it requires a degree of explosivity at times when sheeting in around the bottom mark or at start time, jumping out of tacks in and out of the toe straps"* or *"the boat is really twitchy when going through manoeuvres. Especially for the crew being able to go fast from lying out flat on the wire and then power up through that into a half squat in the middle and then jumping out again"* possibly acknowledging that more research should be completed in this area for elite sailors.

Bojsen-Möller and colleagues (2014) remarked that to maximise righting moment to increase speed in, there are a range of specific boundaries for anthropometry observed in Olympic class sailing. This statement is backed up in the interview analysis where one athlete said *"Every boat requires different heights and weights. I think it's important to choose a class that suits you, that you are the right size for. I know many people that I've raced against that have failed, and part of their failure is their physique"*, as already mentioned in this discussion there appears to be a greater requirement to be within the specific boundary the higher the level of competition "*if you're not tall enough or too big or small you won't make it. You have sailors that are really short that do well and about 50% of regattas and then really averagely in the other half, so you need to be good in all conditions and exceptional in a couple."* Specifically a few interviewees mentioned Leverage, i.e. the ability to use a combination of height, body mass and physical capacity to produce righting moment and therefore speed (Mackie *et al.,* 1999). Two athletes commented: "*if there was someone that was the same as me in every other way apart from they were taller, then they definitely would be better - Well they could make a boat go faster"*, or *"everyone's fitness is fairly high you start to notice some of the physical differences. So you have someone who is 6ft 2 and someone who's 5ft 8 racing against each other, no matter how fit the short of person is they're always going to be giving away leverage which turns into boat speed"*

The importance of competence in fundamental movement skills and general physical characteristics is clearly referenced in developing elite athletes to underpin future sport-specific skill development (Abbott *et al.,* 2002; Jess and Collins, 2003; Gagné, 2004), develop physical athleticism (Lloyd *et al.,* 2015a; Bergeron *et al.,* 2015), reduce injury and illness risk (Lauersen *et al.,* 2014), enhance effectiveness of training hours (Rees *et al.,* 2016; Tucker and Collins, 2012) and ultimately improve skill development (Elferink-Gemser *et al.,* 2010; Kliegl *et al.,* 1989). This on top of improvements in psychological (Lloyd *et al.,* 2015a) and health (Faigenbaum *et al.,* 2013) factors. All-round fitness was the physical raw data theme mentioned by the greatest number of elite coaches and athletes, in line with the above literature comments of elite coaches and athletes included: *"There is a need for all-round fitness"*, just "*having that good base when you're younger*" and how this can impact skill development: "*they don't have a general fitness, a good enough base. So they'll try and do what we're doing, so we're sailing in the morning or whatever and do quite a hard session, and then they're knackered for the rest of the day"* from the ability to withstand the forces on the boat to *"Improve their strength which would help their technical progression".* Similar links were made with a greater level of aerobic fitness preserving cognitive function to support the capacity to learn: "*The physical demands can overtake what they're thinking, so the fitter the person is, the more brain space there will have left to make the decisions*" or "*if you have a really good fitness level, you put your concentration into a more important area*".

The increased requirement for physical athleticism as an elite sailor progresses was evidenced through quotes such as *"it is much easier to get away with it at the Junior level to a certain extent with just reasonable fitness that you will not get away with it in* Youth *classes, no chance" or* "*fitness becomes non-negotiable*". Interviewees referenced the need for physical fitness around injury/illness prevention during training "*So while we'll do another session in the afternoon and they try and keep up with us, and they get ill or injured"*, simply stated by one athlete *"A big one is injury prevention - a big one",* an athlete reflected on ending their career prematurely based on recurring injury *"What I really needed to be told was the injury prevention side of things, which for me was a big problem in my career. My biggest regret is that with injuries I stopped my career earlier than I'd have liked to and felt like I would have spent less time in the last few years with dealing with injuries."* It appears that a key aspect of elite developing sailors is to be as one coach describes to *"be robust and injury free"*. The multiple benefits of all-round fitness is summarised by one of the elite coaches who stated: *"The underlying message is the fitter and faster the sailor is, the better they'll learn and the better they will perform, It is important for sailors to realise that fitness is free speed around the course."*

A key aspect of successful development for elite sailors was around transitions, with a number of elite athletes and coaches referencing the significant steps when progressing through to elite senior participation in a range of components of fitness including: Strength: *"As they work up the ladder the physical side becomes more and more important", "There is a greater amount of strength that they need to just sail the equipment and move the rig around"*, Conditioning: *"everybody suddenly becomes well-conditioned, and everybody's techniques are at such a level that it's very hard to start using your decision-making as you're trapped in between boats and there is no space"* an athlete looked back and said *"If I look back on it now it was such an easy gain it would have been the obvious thing to do … I guess I wish I'd made a bit more of that now and just had a better base",* Aerobic fitness: *"One of our transitioning sailors is probably strong enough, but lacks the aerobic fitness, he* *might be fit enough to do one race, but not three in a row. In his first Olympic level regatta I thought his fitness was pretty good, but as the races went on he was starting to struggle on the last couple of legs due to fatigue from the bigger sail. So fitness again is the key factor"*, All-round fitness: *"[The] 49er is a big step up as it becomes a big platform they need to run around on, a big unstable slidey platform - so the most important stuff is around the agility and strength"* and Power: *"You could say it is about building the speed in the 29er and then adding power and the force in the 49er".* Even at the elite senior level the differences between classes is presented by one athlete: *"I'm not convinced about the need to excel [in fitness], I think the demands of Olympic sailing are that you need to be fit, we're not talking about creating a rower - some of the boats in the Olympics don't even require you to be fit, like the 49er helm or the 470 helm, you don't even need to fit. Boats like the Finn you do".* From the interview analysis it is clear that the demands differ when transitioning up the pathway and between classes therefore an athlete's needs will vary and sports science support must be tailored individually.

3.4.1 Strengths and Limitations

The strengths of this study are that this is the first research completed to identify key characteristics of successful elite development in sailing, the use of a sample of experienced elite pathway coaches across a range of sailing classes plus corroboration with a high level elite sample of athletes who have all been ranked within the top two in the world including Olympians and multiple Olympians gives perspective on what it takes to succeed, but also on the sailors who were not successful. The process of trustworthiness with allowing elite coaches to review the analysis before a follow-up interview ensured that a comprehensive list of characteristics were obtained and not just limited on a one-off process, both athletes and coaches were able to view their comments before the end of the interview and were able to add any more comments. The first and third researchers were experienced in sailing which meant the interviews were able to be completed with empathy and the triangulation of analysis was robust. The sample of elite coaches and athletes comprised of males and females who had experience sailing and/or coaching a wide range of single-handed boats/boards and double-handed boats across all groups of sailing classes.

Limitations include the restriction of further analysis to purely physical characteristics, it is clear from the analyses in Figure 3.1 and Figure 3.2 that successful elite development is based on a wide range of factors. Though this initial process paves the way for further analysis of these factors and the further interaction between them in future research. As with all retrospective recollection there is a chance of memory bias, or rosy retrospection (Mitchell and Thompson, 1994) that could possibly confound the results. Although the sample was of a high quality, a limitation could be from the sample size and quality although there is always a trade off as if purely multiple-Olympians were selected the sample size would be dramatically lower, it would reduce the number of classes sailed, and limit the natural individual variation in elite trajectories. A further development would be to compare sailors from this study to those who were not successful, or to add further numbers of sailors to compare between characteristics of elites and super-elites.

3.5 Practical applications

The main findings of this study are that there is a broad level of agreement between a sample of elite pathway coaches and top elite athletes successful development in elite sailing is based on a wide range of factors within the physical domain, categorised into Components of Fitness and Anthropometry. Variety exists between the relative importance of these factors when transitioning through stages of development, and between different sailing classes.

These findings informed the physical profiling battery utilised by the British Sailing Team Olympic pathway ensuring inclusion of the key physical characteristics outlined within this study. A number of these physical factors have been shown to differentiate between elite and non-elite sailing performance (Callewaert *et al.,* 2014b) and relate to performance rankings which could serve as key indicators towards elite progression (Lidor *et al.,* 2009; Pearson *et al.,* 2006). These characteristics profiled longitudinally while considering for maturation status (Vaeyens *et al.,* 2008) could enable the Olympic pathway to establish elite benchmarks to track sailors' physical development, and therefore direct resources and support effectively to support development created around individual needs (Allen *et al.,* 2014).

Chapter 4 Physical Testing Battery

4.1 Introduction

The previous chapter identified the key physical characteristics of transition to successful Olympic sailing. This chapter details anthropometrical procedures used through all studies in this thesis, and the methods of assessing components of fitness within the British Sailing Team's Olympic pathway Physical Testing Battery which were reinforced through the findings of the previous chapter. Additional information is provided related to the suitability and reliability for each test.

After the first year of data collection, the existing methods of assessing anthropometry, agility, lower body strength and aerobic fitness were confirmed within the testing battery through communication between the author and the sport as being reliable and appropriate. Due to the discontinuation of the Concept II Dynamometer (DYNO) strength trainer (Concept2, Nottingham, UK) during this year it was required that new tests were investigated to replace the previous method to assess upper body pushing and pulling strength. The aim of creating the testing battery was to improve understanding of physical development within the British Sailing Team's Olympic pathway through engagement in a longitudinal data collection project within British Sailing to track the physical characteristics of Olympic sailors – this thesis will present and interpret the findings of the initial five-years of the longitudinal data collection process.

4.2 Anthropometry

In rare instances where anthropometrical measurements were not collected by the lead researcher, experimenters accredited at level one with the International Society for the Advancement of Kinanthropometry (ISAK) were used, to ensure standardisation. Procedures were conducted in accordance with the International Standards for Anthropometric Assessment (Stewart *et al.,* 2011) developed by ISAK. As part of the ISAK accreditation Technical error of measurement (TEM) is required to be below 1.5% (inter-rater) and 1.0% (intra-rater) for stature and bodymass assessments. The lead researcher post-accreditation recorded relative TEMs of 0.05 and 0.08% for height and bodymass respectively assessed through 20 complete anthropometrical profiles.

4.2.1 Height

All measures of height were recorded using a Harpenden Portable Stadiometer (Holtain Ltd., Crosswell, UK) to the nearest 0.1 cm. The stretch stature method was used for all height measurements, where the participant's head was placed in the Frankfort plane and upward pressure applied through the mastoid processes. Measurement was recorded at the end of a deep inspiration with headboard pressed firmly down on the vertex of the skull.

Standing height was measured with participants stood barefoot with both feet flat on the floor with back, buttocks and heels against the vertical board of the stadiometer. Measurement of seated height was performed with the participant seated on the base of the stadiometer with feet on the floor and knees bent sufficiently so that the upper body was positioned correctly as per standing height measurement.

4.2.2 Body mass

Participants were weighed barefoot (CPW 150, Adam Equipment Co Ltd., Milton Keynes, UK) in minimal sports clothing (t-shirt and shorts) and were instructed to remain still positioned in standing posture with hands by sides. All measurements were taken in the morning before any exhaustive exercise and accurate to ± 0.05 kg.

4.2.3 Armspan

Armspan was measured with participants stood upright, with weight distributed evenly across both feet. Participants were instructed to spread arms out to the sides in a straight horizontal line with shoulders relaxed. Measurement was recorded using a tape measure (Silverline, UK) to the nearest centimetre.

4.3 Components of Fitness

The remainder of this chapter describes the process and testing utilised by the British Sailing Team's Olympic pathway. Informed consent was received from parents and sailors as part of acceptance of a place within the Olympic pathway and/or attendance at physical profiling sessions. Each yearly season a maximum of two pathway profiling sessions were conducted per sailor (Winter: September to December, and Spring: February to April).

Sailors were advised on how to prepare for physical profiling through by use of a profiling document (Appendix 7). This included: attending all sessions in a fully hydrated state (i.e. light urine colour), ad-libitum water and food intake allowed during testing sessions. At least one hour post-prandial, and having abstained from caffeine consumption that morning. In addition, participants were asked to refrain from strenuous exercise and for at least 24 hours prior to the sessions. All testing sessions were completed at the same time of day, commencing between 8.00 am and 10.00 am and to avoid influence of circadian rhythm (Hayes *et al.*, 2010). Testing was performed in groups of up to 60 sailors at a time indoors in sports halls. Checks on floor surface grip were completed pre-testing, with additional sweeping and mopping if necessary. Anthropometrical measures were conducted as described in section 4.2.

4.3.1 Reliability

To be able to deliver physical profiling twice a season routinely within the Olympic Sailing pathway programme structure, multiple testers were recruited to staff the days, resulting in different individuals running tests from one profiling session to another. Access to elite sailors to perform either repeated trials of profiling tests on same day/consecutive days or weeks without invalidating scores due to interference from sailing training was not possible. This situation provided a complex task to understanding reliability with the pathway. To increase understanding of reliability within the physical testing battery analysis, test-re-test within-session was calculated for tests that used multiple trials in profiling sessions (i.e. T-test and standing long jump (SLJ), see Table 4.1 and Table 4.2) reporting on results collected on three separate sessions using different testers across a range of ages (Session one: n = 32, age 16.3 ± 1.08 years, Session two: n = 36, age 13.5 ± 0.88 years, session three: n = 67, age 13.8 ± 1.05 years). For further understanding for these tests, or for tests where within- or between-session reliability was not measured, the following sections report on previous literature that investigated reliability using the same protocols. Equations for calculation of reliability are presented in equations (1) to (5):

Typical Error of Measurment (TEM) calculated by the dividing the standard deviation of the difference between measurements by the square root of 2:

$$TEM = \frac{S.D.(diff)}{\sqrt{2}} \tag{1}$$

Relative Typical Error of Measurement (TEM %) displayed as percentage:

$$TEM\ (\%) = \left(\frac{TEM}{Score}\right) x\ 100 \tag{2}$$

Confidence Intervals (CI) calculated as 95% by multiplying the standard deviation of the difference between measurements by plus and minus 1.96:

$$CI = S.D.(diff)\ x \pm 1.96 \tag{3}$$

Coefficient of Variation (CV) calculated by dividing the standard deviation by the mean, expressed as a percentage:

$$CV = \left(\frac{S.D.}{\bar{x}}\right) x\ 100 \tag{4}$$

Smallest Worthwhile Change (SWC) calculated by multiplying the standard deviation of the difference between measurements by 0.2:

$$SWC = S.D.(diff) x\ 0.2 \tag{5}$$

4.3.2 T-test (Agility)

The categorisation of agility within sailing development from Chapter 3 related to quick accurate movements and general movement ability. The rationale for inclusion of agility in the Physical Testing battery can be found within literature review sections 2.5.1 and 2.5.2.2, plus added context from coach and sailor quotes in section 3.3.4.5. The T-test was chosen as it measures the ability to perform four directional movement accurately on feet through maintenance of balance and body control (Semenick, 1990), and has previously been shown to be a reliable test (Munro and Herrington, 2011; Pauole *et al.*, 2000; Sporis *et al.,* 2010).

Within-session reliability of T-test (two trials) from three separate sessions are displayed in Table 4.1 displaying similar reliability between different testers and age groups. The coefficient of variation (CV) across these sessions (1-2%) is similar to the 3.3% previously reported (Sporis *et al.,* 2010). Very good reliability of T-test performance has been stated in a range of studies: Pauole and colleagues (2000) reported intra-class correlation coefficient (ICC) using one-way ANOVA between one and three repeated trials during the same session of 0.94 to 0.98 in 303 university students (male and female) from a range of activity levels. Similar results were observed in a sample of 150 national level Serbian footballers across three trials with ICC of 0.928 (Sporis *et al.,* 2010). Munro and Herrington (2011) investigated between-session reliability in 22 physically active university-aged males and females, conducting T-tests on three consecutive weeks, and found similar ICC in males (0.96) and lower in females (0.82) with smallest detectable differences of 0.58 and 0.48 sec respectively.

Table 4.1 Within-session reliability of T-test on three separate occasions

	Session One n = 32	Session Two n = 36	Session Three n = 67
TEM (sec)	0.35	0.41	0.40
TEM (%)	3%	3%	3%
CI (+/-)	0.98	1.14	1.10
CV (%)	1%	1%	2%
SWC (sec)	0.10	0.12	0.11

Note: TEM – Typical error, CI – 95% Confidence interval, CV – Coefficient of variation, SWC – Smallest worthwhile change

The T-test layout was set-up as per Semenick (1990). Cones were arranged in a 'T' shape with 10 yards (9.14m) between the start/finish line and middle cone, and 5 yards (4.57m) between the middle and left and right cones (Figure 4.1). Time taken to complete the test was recorded using timing gates (Brower Timing Systems, Draper, Utah) placed 3 m apart at either end of the start/finish line at a height of 1 m. After a full speed demonstration, participants were taken through a standardised practice warm-up using a 10 x 10-yard grid comprising of the movements allowed in the test. Progressively increasing intensities (50, 75 and 100% of maximum speed) of forward and backwards running and left/right sidestepping were completed.

Once warmed up, participants started 0.5 m behind the start line and were instructed to sprint 10 yards as fast as they could to the middle cone, touch it with their right hand and side-step 5 yards to the left cone and touch with their left hand. Then side-step 10 yards right touching the right cone with their right hand before side-stepping left to the middle cone. Participants must touch the middle cone with their left hand before back pedalling 10 yards through the start/finish line at maximum speed. A deceleration area 20 yards long was cleared for participants to allow them to slow down at their own pace.

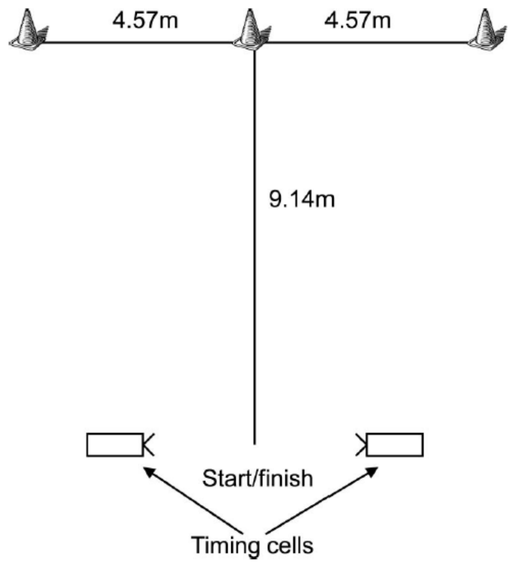

Figure 4.1 Layout of T-test according to Semenick (1990) taken from Munro and Herrington (2011)

Scores were not counted if participants failed to touch all of the cones with the designated hand, crossed their legs over while side-stepping, or failed to face forwards during the entire test. Two trials were completed during testing as previous literature exhibited a requirement for at least two maximal trials to negate a learning effect within between genders and level of physical fitness (Munro and Herrington, 2011; Pauole *et al.* 2000; Sporis *et al.,* 2010). Participants were given at least two minutes rest between trials, with the fastest time recorded.

4.3.3 Standing Long Jump (Lower body strength)

Lower body strength, specifically in knee extensors, and the ability to sustain this strength for long durations has been shown to be important across the range of sailing classes (see 2.5.1, 2.5.2 and 3.4). Further rationale for selection of this test from coach and sailor quotes can be found in section 3.3.4.2 and 3.3.4.4. The standing long jump (SLJ) was chosen as it has been reported to have a strong association with a range of lower body strength tests (Castro-Piňero *et al*., 2010), has been shown to be reliable (Españа-Romero *et al.,* 2010; Fernandez-Santos *et al.,* 2015; Moresi *et al.,* 2011; Ortega *et al.,* 2008; Seitz *et al.,* 2016), and it is a practical solution for large scale fitness testing due to low cost, equipment and time resource requirements.

Within-session reliability of SLJ (three trials) from three separate sessions are displayed in Table 4.2 displaying similar reliability between different testers and age groups. An increase was observed between jumps one and two (2-1), however no further difference was observed between each of the combinations of tests from the second jump onwards (3-2, 3-1), exhibiting a plateau which gives confidence of a true score within the number of trials completed. This is supported by two studies: Seitz *et al.* (2016) that found no greater increase from repeated trials after the second trial in fourteen university aged (18.4 ± 0.8 years) rugby league players (change in score from baseline at jump 2: 1.0 ± 1.6%, jump 3: 1.4 ± 2.9%, jump 4: 0.8 ± 1.4% and jump 5 1.4 ± 2.0%). Moresi *et al.* (2011) found good levels of reliability in female junior national level track and field athletes across three trials with at least 30 seconds recovery, revealed through ICC of 0.93 and CV of 3.4%, similar to the observed in this study. Research findings investigating reliability of SLJ in youth populations have focused in between-session reliability primarily calculating the inter-trial difference to establish error. Acceptable levels of reliability were found in non-elite populations with no significant differences observed using: 138 school children seven days apart, aged 6 to 18 years in PE classes (0.33 ± 13.4 cm; España-Romero *et al.,* 2010), 363 healthy white children seven days apart, aged 6 to 12 years (-0.71 ± 10.41 cm; Fernandez-Santos *et al.,* 2015) and 123 healthy adolescents two weeks apart, aged 13.6 ± 0.8 years (-0.3 ± 12.9 in males and 0.3 ± 9.0 cm in females; Ortega *et al.,* 2008).

Table 4.2 Within-session reliability of SLJ on three separate occasions

	Session One n = 32				Session Two n = 36				Session Three n = 67			
	2-1	3-2	3-1	Mean	2-1	3-2	3-1	Mean	2-1	3-2	3-1	Mean
TEM (m)	0.08	0.07	0.06	0.07	0.04	0.04	0.06	0.05	0.04	0.05	0.05	0.05
TEM (%)	4%	4%	3%	3%	3%	3%	4%	3%	3%	3%	3%	3%
CI (+/-)	0.15	0.14	0.12	0.14	0.09	0.09	0.12	0.10	0.09	0.11	0.11	0.10
CV (%)	2%	2%	2%	2%	2%	3%	3%	2%	2%	2%	3%	2%
SWC (m)	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.02

Note: TEM – Typical error, CI – 95% Confidence interval, CV – Coefficient of variation, SWC – Smallest worthwhile change

Participants were instructed to complete whole body mobility exercises prior to their first SLJ consisting of arm circles, trunk rotations, leg swings and heel kickbacks. All jumps were completed on a purpose-built non-slip mat (SBP Products, Montreal, Canada) that was affixed to the floor. Participants placed their feet with toes behind the take-off line, and explosively pushed off with a two-foot take-off with arm swing and jumped as far as possible. For the jump to count the participant had to land on their feet and remain standing – if they became unbalanced they were able to put a hand down for balance as long as their feet didn't move. Each participant completed three maximal trials with the best score recorded in metres (m), distance measured was from the back of their rear heel to the take-off line.

4.3.4 20-metre shuttle run test (Aerobic capacity)

High to very high aerobic fitness have been reported in sailors at pathway and Olympic level (section 2.5.2.2 and 2.5.1 respectively). These findings were supported during coach and sailor interviews, as quotes highlighted the benefits of aerobic fitness in successful sailing development through supporting training and the acquisition of skill, aiding performance and preserving cognitive function on the water (see section 3.3.4.3). The multistage 20-metre shuttle run test (20 m SRT) was selected to assess aerobic fitness as previous research has found the test to be reliable (Espaňa-Romero *et al.,* 2010; Leger *et al.,* 1988; Liu *et al.*, 1992; Ortega *et al.,* 2008), and is the most appropriate test for assessing large numbers of athletes combined with low cost and equipment requirements.

The original study of Leger *et al.* (1988) found the 20 m SRT to be reliable in children and adults using simple regression analysis (r = 0.89 and 0.95 respectively), with no significant difference ($P > 0.05$) between test and re-test one week apart using paired t-tests. Artero *et al.* (2010) conducted a systematic review of reliability in field-based fitness tests, including 20mSRT screening studies from 1990 to 2009. The authors of this review rated quality using a three-level method including: description of participants, time between measurements and appropriateness of statistics. Reliability is shown in this section purely from high quality studies: Liu *et al.* (1992) found high ICC 0.93 for the number of laps completed one week apart in 20 boys and girls aged 12-15 years, mean laps completed were found to not be different using ANOVA ($F_{[1,19]} = 2.58$, $P \geq 0.13$). No significant inter-trial difference were observed in 138 school children seven days apart, aged 6 to 18 years in PE classes (0.05 ± 1.0 stages; Espaňa-Romero *et al.,* 2010), or 123 healthy adolescents two weeks apart, aged 13.6 ± 0.8 years (-0.1 ± 1.5 stages in males and 0.0 ± 1.1 stages in females; Ortega *et al.,* 2008).

The physical testing battery always concluded with the 20 m SRT for aerobic fitness, as conducted by Leger *et al.* (1988). Participants ran shuttles across a 20 m course at progressively faster speeds to a set of audible beeps, starting speed was set at 8.5 $km.h^{-1}$

increasing by 0.5 $km.h^{-1}$ each minute until exhaustion or if they couldn't keep up with the pace. The last audible stage completed was counted as the recorded score.

4.3.5 Required progression of Physical Testing Battery

The above sections (4.2 to 4.3.4) critique the continuing assessments within the physical testing battery. It was concluded that modifications to the battery were required due to the Concept II DYNO became discontinued and therefore did not provide a long term solution, and the accuracy of the current maturity assessment had not been investigated or compared against other methods. The following two chapters describe the process of assessing the suitability of new test choices, investigating reliability, validity and accuracy of these measures.

Chapter 5 Reliability, validity and interrelationships of upper-body strength assessments

5.1 Introduction

The previous chapter detailed the general methods that occur throughout the thesis, and described the current physical testing battery. This chapter studies the reliability, validity and interrelationships between the current upper body strength tests and field-based tests with gold standard assessments. With the aim of selecting long-term upper body push and pull strength test replacements for the physical testing battery, as the current testing equipment became discontinued.

The measurement of strength is integral to a complete physical profile. The benefits of strength have been observed in a health setting such as completion of everyday actions or a decreased mortality rate (Ruiz *et al.*, 2008), and in elite sport, where strength training has been shown to be an essential aspect of physical preparation (McGuigan *et al*, 2012) highlighted from improvements in injury reduction and core stability (Young, 2006). Numerous methods are employed to assess characteristics of muscular strength including; Isometric peak force (PF), one repetition maximum lifts (1RM), muscular endurance using repetitions to failure at a set percentage of 1RM, or field tests based on bodyweight exercises.

When deciding on the suitability of a strength assessment, it should be valid and reliable. Validity is defined in this study by possessing a strong relationship between the value produced and the value of a gold standard measure (Verdijk *et al.,* 2009). Reliability is defined by a measure being reproducible when repeated trials are conducted (Hopkins, 2000). When assessing strength of contralateral upper body push and pull movements, laboratory-based strength testing, such as the production of isometric PF is considered the gold standard of assessing strength due to its very high reliability and internal validity (Verdijk *et al.,* 2009). The most common upper body isometric assessment is the supine bench press with elbow angle set at 90°, and it has been found to be reliable with Intra Class Correlations (ICC) ranging from 0.82 to 0.95 (Kilduff *et al.*, 2002; Pryor *et al.*, 1994). Debate exists over the criterion strength method to assess strength, isometric PF has been challenged as it lacks external validity due to static nature of contractions not being representative of real-world movements (Blazevich and Cannavan, 2007; McMaster *et al.*, 2014). In the absence of a laboratory, RM testing has long been considered a reference standard for assessing dynamic maximal strength (Invergo *et al.,* 1991) and has also been considered a gold standard in strength assessment (Levinger *et al.,* 2009).

1RM testing is a popular method of assessing strength employed outside of the laboratory (Verdijk *et al.,* 2009), upper body assessment is typically measured using the Bench Press and Bench Pull exercise (Pearson *et al.,* 2009). Previous research has demonstrated very high test-retest reliability in Bench Press performance in trained and untrained populations, with ranges of ICC of 0.98 to 0.99 (Invergo *et al.*, 1991; Levinger *et al.*, 2010; McGuigan *et al.*, 2010; McGuigan and Winchester., 2008). There is a dearth of research on the reliability of upper body pulling strength assessments, with the majority of published work using elite or sub-elite rowers. Test-retest reliability in this movement has also been demonstrated to be very high (ICC > 0.96) from the laboratory of Lawton and colleagues (2013) employing a 6RM bench pull, which is supported with 1RMs in rowers and in an untrained sample (ICC = 0.99) (Bell *et al.*, 1993; Levinger *et al.*, 2010).

Relationships between measurements of isometric and dynamic performance have yielded a range of findings. Haff *et al.* (2005) investigated the relationship between isometric mid-thigh pulls (MTP) and Olympic lifting 1RMs in elite female weightlifters. Pearson product moment correlations (r) of 0.93 and 0.80 were found between the MTP and Snatch and MTP and combined total, respectively. In support, McGuigan *et al.* (2010) found near perfect relationships with MTP and 1RM squat (r = 0.97) and MTP and bench press (r = 0.99) in recreationally trained men. Conversely poor correlations (r < 0.5) between isometric PF and athletic performance have also been reported (Blazevich and Cannavan, 2007). Two studies that investigated upper body isometric and dynamic bench press movements found small to moderate relationships: Ignjatovic *et al.* (2009) compared isometric bench press with the bar 2-5 cm above the chest and an elbow angle of 135° with a submaximal prediction for 1RM (r = 0.16 and 0.33), while Murphy and Wilson (1996) observed moderate correlations (r = 0.47 to 0.55) in healthy males performing isometric maximal efforts at elbow angles of 90 and 120° with a seated medicine ball throw.

In a recent review conducted by McMaster and colleagues (2014) it was proposed that profiling tools involving weight lifting are more suited to monitoring and adapting resistance training programmes than performance, as the actions involved may not represent strength specific to the sport. With this in mind, field tests involving moving the athlete’s own bodyweight may be more representative of sporting or real-world situations. Field testing can be useful when looking to assess strength relatively quickly in large samples without the need for expensive equipment or extensive tester training; however the application of field testing is limited as it lacks the rigors of physiological measurement in the laboratory.

Maximum repetitions of push-ups and pull-ups are currently used to measure upper body strength endurance (Negrete *et al.,* 2010); however these movements have been modified into a number of derivatives including female- and child-specific movements (Baumgartner *et al.*, 2002), which makes comparison across studies difficult. Push-ups have displayed good to very good reliability across a number of variations; maximum repetitions in a minute (ICC = 0.93/r = 0.96-0.99; Invergo *et al.*, 1991; Jackson *et al.*, 1994), bent-knee push-ups using a female sample (ICC = 0.83; Wood and Baumgartner, 2004) and in 15-sec bursts (ICC = 0.989; Negrete *et al.*, 2010). Modified pull-ups have received less research attention with variations including 15-sec bursts of modified straight leg pull-ups, which demonstrated very high reliability (ICC = 0.958; Negrete *et al.*, 2010) and straight leg pull-ups in children using an elastic band to record reps with a reduced range of motion achieving very high norm-referenced reliability using intraclass correlations from ANOVA *(R* = 0.97-0.99) (Saint Romain and Mahar, 2001).

Research investigating the relationship between field testing methods and 1RM shows mixed results. When comparing push-up variations, correlations range between small and very large (r = 0.23 – 0.87) (Baumgartner *et al.*, 2002; Invergo *et al.*, 1991; Jackson *et al.*, 1994; Mayhew *et al.*, 1991; Wood and Baumgartner, 2004). Explanations for this range of findings possibly arise from differences in push-up variations, tempo, sample characteristics, and method of 1RM chosen, from free weight or resistance machine based exercises. Modified pull-ups have produced moderate to strong relationships with 1RM testing when corrected for bodyweight (r = 0.60 – 0.79) (Pate *et al.*, 1993).

Weight-bearing testing methods present the potential of future standardisation of protocols in the field: The Revised push-up as employed by Baumgartner and colleagues (2002) and the Vermont Pull-up (VMPU) have shown the most promise for reliability and validity. Revised push-ups displayed very strong reliability (ICC = 0.90 – 0.99) and validity with bench press performance (r = 0.80 – 0.87) and VMPUs were the only pull-based movement to exhibit high levels of significance in a standardised regression equation to the sum of 1RMs (r = 0.40, *P* = 0.04) compared to pull-ups, flexed arm hang and New York modified pull-ups (Woods *et al.*, 1992). The flexed-arm hang and VMPU also had the lowest number of zero scores. Concerns have been expressed with the high possibility of zero scores in weight-bearing tests, with more found in full push-ups versus a bent-knee modification (Wood and Baumgartner, 2004).

The current upper body push and pull strength tests within the British Sailing Team's Olympic pathway have used the Concept II dynamometer (DYNO). There has been little research investigating the use and reliability of this equipment, the only reference cites DYNO use in rowers and data from the laboratory of Lawton and colleagues has shown reliability to be very high (ICC = 0.96) (Lawton *et al.,* 2013). Correlations between a seated DYNO pull and 6RM bench pull in a sample of elite heavyweight rowers was large (r = 0.60 – 0.66) (Lawton *et al*., 2013). The Concept II DYNO has the potential to be very useful in field testing scenarios due to the portability and ease of test administration (Lawton *et al.,* 2012), which is one of the main reasons for its initial choice within the British Sailing Team's Olympic pathway.

The aim of this study was to investigate the reliability, validity and interrelationships of upper body tests of muscular strength comprising of: 1RMs, isometric PF, maximum repetitions of VMPUs and Revised Push-ups, and maximum force production using a Concept II DYNO in recreationally trained men and women to identify the most suitable strength assessments within the physical testing battery for the British Sailing Team's Olympic pathway. 1RMs were chosen as the gold standard in line with Levinger *et al.* (2009). For the remainder of this thesis VMPUs will be referred to as Supine Pulls, and Revised Push-ups referred to as Press-ups.

5.2 Methods

5.2.1 Participants

Twenty-six participants volunteered to participate in the study (male *n* = 17, female *n* = 9), age: 23.0 ± 3.3 years, height: 178.2 ± 4.0 cm and body mass: 77.5 ± 12.5 kg. For inclusion in the study participants must have had resistance training experience and be regularly adhering to physical training. All participants were of an active background and were free from any known injury, which was confirmed by completion of a medical questionnaire. The inclusion criteria was selected in young adults, as to resemble the training characteristics of elite pathway sailors, i.e. active, moderately trained males and females with minimal resistance training experience. An elite pathway sailing sample was not achieved, due to the inability to book in sessions at regular time slots to the gym within a school week, this would have been the only option as typically sailing at various venues takes priority on weekends.

Participants provided their written, informed consent following a verbal and written explanation of the procedures and potential risks of the study. Approval for the study was granted by the University of Chichester Research Ethics Committee.

5.2.2 Procedures

Relationships between and the validity and reliability of various methods of assessing upper body strength in recreationally trained males and females. Two main testing sessions were completed and analysed in a test-re-test design after two familiarisation sessions using the same protocol; a) Maximal dynamic strength was determined by 1RM Bench Pull and 1RM Bench press, b) PF data from a prone isometric upper body pull (ISO-Pull) and supine push (ISO-Push), c) maximum number of repetitions completed for Supine Pulls and Press-ups, and d) maximal force on a seated pull (DYNO-Pull) and push (DYNO-Push) using a Concept II dynamometer.

Participants were instructed to attend all sessions in a fully hydrated state (i.e. light urine colour), at least two hours postprandial maintaining similar diets in the 12-hours pre-testing, and having abstained from caffeine consumption that morning. In addition, participants were asked to refrain from strenuous exercise and alcohol consumption for at least 48 hours prior to the sessions (see Appendix 6). Participants attended four 2-hour sessions (2 x Familiarisation FAM1/FAM2 and 2 x Testing TEST1/TEST2) where they completed the same series of tests to determine aspects of upper body strength (Figure 5.1). All testing sessions were completed at the same time of day, commencing between 8.00 am and 10.00 am and between 20 and 22°C (Griffin 76mm Thermometer, Thermo Fisher Scientific Inc.) to avoid influence of muscle temperature and circadian rhythm (Hayes *et al.*, 2010). Ad-libitum water intake was allowed during testing sessions.

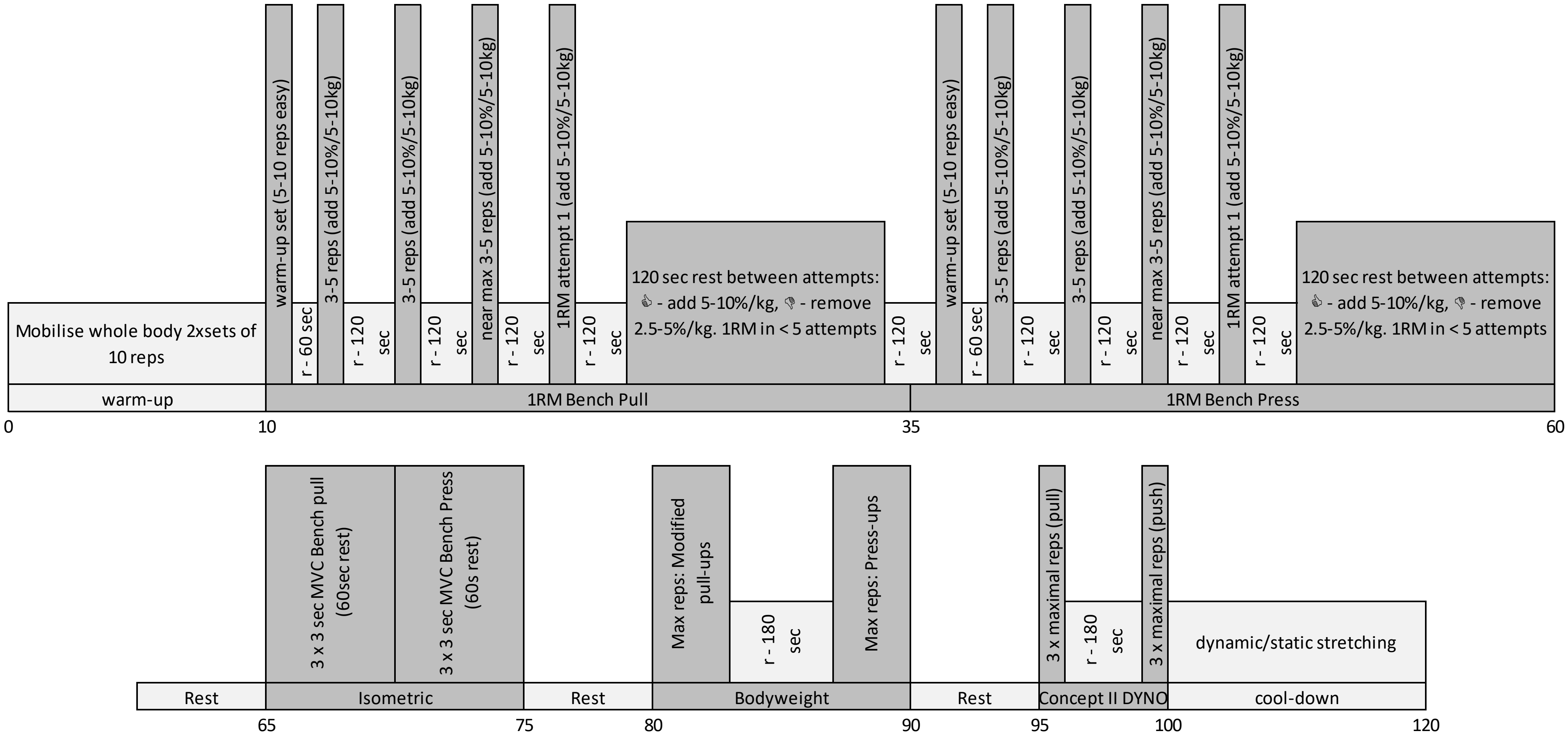

Figure 5.1 Schematic representing testing sessions. Note: numbers along x-axis refer to time in mins, MVC – Maximal Voluntary Contraction, r - rest

Anthropometry. Standing height and bodymass were measured using the methods detailed in Chapter 4.2.

1RM Testing. 1RM scores were obtained following a standardised protocol (Earle, 1999). For 1RM Bench Pull participants lay prone on a padded bench which was adjusted for height using plyometric boxes (Powerlift, Conner Athletics Products Inc., USA), set at a height that would allow participants to grip the barbell whilst displaying full elbow joint extension with the bar on the floor. The lift was only deemed successful when the barbell made contact with the bench below the participant's mid-chest. Three minutes rest was given after completion of each attempt to ensure the effects of fatigue were not observed based on the guidelines of Willardson and Burkett (2006). 1RM Bench Press was obtained in the standard supine position with both feet in contact with the floor, participants were instructed to lower the bar down to touch the mid-chest then press the weight until the elbows were fully extended, maximum load (kg) lifted on a successful repetition was recorded.

In terms of assessing validity for Supine pulls and Press-ups it was decided to add a 1RM calculation relative to bodymass (rel1RM Bench Pull and rel1RM Bench Press). This was chosen due to the two bodyweight-dependent nature of the tests, therefore the gold standard measure should reflect strength related to participant bodymass.

Isometric testing. Peak ISO-Pull and ISO-Push force was measured using a Model 615 S-Type load cell (Tedea-Huntleigh Europe Ltd, Cardiff, UK) which comprised of four strain gauges bonded to an S-shaped metal core in a bridge configuration. The load cell was affixed securely to a sheet of plywood placed on the floor, with an adjustable height bench placed on top of the ply sheet (Figure 5.2). The differentiated analogue output was amplified (Bridge Amp ML221, AD Instruments Ltd, Oxford, UK) before being digitised (Powerlab 4/30, AD Instruments, Oxford, UK) at a sampling rate of 1000 Hz. The digital signal was passed to computer for display, storage and further analysis using Chart Pro Version 5 (AD Instruments Ltd, Oxford, UK). Bench height and position was adjusted to ensure an elbow angle of 90° for both ISO tests, which was assessed using a goniometer. Participants were instructed to maintain a constant elbow angle for the duration of the trial; if the angle was not constant the trial was discarded. Load data (mV) was converted to kg using linear regression through the weighing of calibrated weight plates up to 100 kg, for calibration calculations see Appendix 2.

ISO-Pull force was determined by instructing participants to lie prone on the adjustable height bench and pull on an immovable bar attached to the load cell. Participants performed two warm-up efforts of 50 and 75% of their perceived maximum effort, following this participants performed 3 x 3 sec maximal efforts with force produced as quickly as possible (Haff et al., 1997). Participants had one minute passive rest between efforts, three minutes rest was given between ISO-Pull and ISO-Push tests (Willardson and Burkett, 2006). The highest value of the maximal trials was used for subsequent analysis. ISO Push force was measured by attaching the immovable bar to the horizontal bar of a smith machine (Marcy SM600, Marcy Fitness, UK) using chains at each end. Participants were instructed to lie supine on the adjustable bench positioned so that elbows were at 90° when pushed against the immovable smith machine bar with the chains in tension. The greatest force (kg) produced in a single repetition was recorded.

Figure 5.2 Isometric testing set-up

Bodyweight testing. Supine pulls were set-up with each participant adopting a lying supine position under a horizontal bar of a smith machine with adjustable height settings used for ISO testing (Figure 5.3). For correct bar height, arms were placed in a vertical position with fingers touching the back of the bar one hand outside shoulder width, using a pronated grip with shoulder blades protracted so shoulders were off the ground with the upper back still in contact. Once the bar height was correctly adjusted the participant bent the left leg so that the medial malleolus of the ankle lined up with the medial joint line of the right knee, the right foot was then brought up in line with the left. Shoulder blades were retracted to raise the participant off the ground and then commenced repetitions at a pace of one second up and one second down until failure or technique was not maintained i.e.

unable to maintain body alignment, chest not touching the bar on each repetition, excessive hip action or if performing repetitions too fast or slow. All repetitions that were completed with appropriate technique were counted.

Figure 5.3 Starting and finishing position for Supine pull test

The Press-up test was conducted in line with the Revised Push-Up Test Protocol recommendations of Baumgartner *et al.* (2002) started with participants lying on the floor in a prone position, with feet hip width apart, hands placed in line with the outside of the shoulders and elbows pointing towards the ceiling. The participant braced the hips and trunk while simultaneously lifting the knees so that the legs are fully extended, then pressed up to top position with extended elbows while maintaining body alignment with head in neutral position. For starting and finishing positions of each repetition see (Figure 5.4). At a pace of one second up and one second down the participant continued performing repetitions to failure, or when technique was not maintained i.e. unable to maintain body alignment, repetitions performed too fast or slow or not performing full range of motion with chest touching the floor in between every repetition. All repetitions that were completed with appropriate technique were counted.

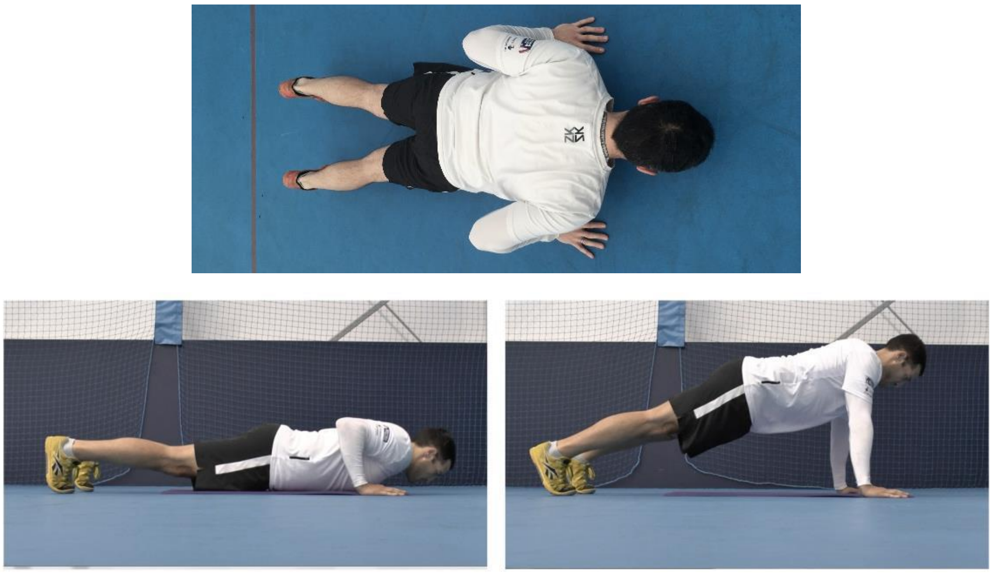

Figure 5.4 Starting and finishing positions for the Press-up test

Concept II Dynamometry. Maximal dynamic upper body force was also assessed using a Concept II Dyno strength trainer (Concept2, Nottingham, UK) with the drag factor set to 240 using a minimum of 25 repetitions. DYNO-Pull was performed with participants taking a pronated grip with elbows fully extended and pulled the carriage with maximal effort until the bar touched the chest. DYNO-Push was performed starting with the elbows at 90°. For both dynamometer assessments the same warm-up and testing protocol was used, which consisted of three submaximal repetitions interspersed with five seconds rest; following this three maximal effort repetitions were performed every five seconds, with the largest force (kg) value recorded.

Figure 5.5 Image of Concept II Dyno strength trainer

5.2.3 Data Analysis

A Windows-compatible version of IBM SPSS Statistics 20 (IBM Corporation, USA) was used for analysis of data. All variables included within this study were found to be normally distributed, as were found to have skewness and kurtosis of <2. Test-re-test reliability of all variables was calculated using a 2-way mixed Intraclass Correlation (ICC). Validity of bodyweight and DYNO tests were assessed using Pearson's product-moment correlation coefficient (r) with 1RM Bench Press and Bench Pull tests (plus rel1RM Bench Pull and rel1RM Bench Press) used as gold standard measures. Interrelationships between other variables were also assessed using correlations (r). The magnitude of the correlations reported were as follows: trivial (<0.1), small (0.1 – 0.3), moderate (0.3 – 0.5), large (0.5 – 0.7), very large (0.7 – 0.9), nearly perfect (>0.9) and perfect (1.0) (Hopkins, 2000). All data are reported as mean ± 1 S.D. unless indicated otherwise. One-way repeated measures ANOVA were completed to assess the impact of any learning effect across the four testing sessions (FAM1 – FAM2 – TEST1 – TEST2).

5.3 Results

One-way repeated measures ANOVA revealed that there was no learning effect between TEST1 and TEST2 in any strength assessments ($P > 0.065$) therefore two familiarisation trials were sufficient for a plateau in performance to be observed in all tests (Figure 5.6). Differences were recorded only between FAM1 and FAM2 trials in 1RM Pull, rel1RM Bench Pull and Supine pulls ($P = 0.007$, 0.010 and 0.004 respectively) and also in 1RM Bench Press and rel1RM Bench Press between FAM2 and TEST1 ($P = 0.025$ and 0.021).

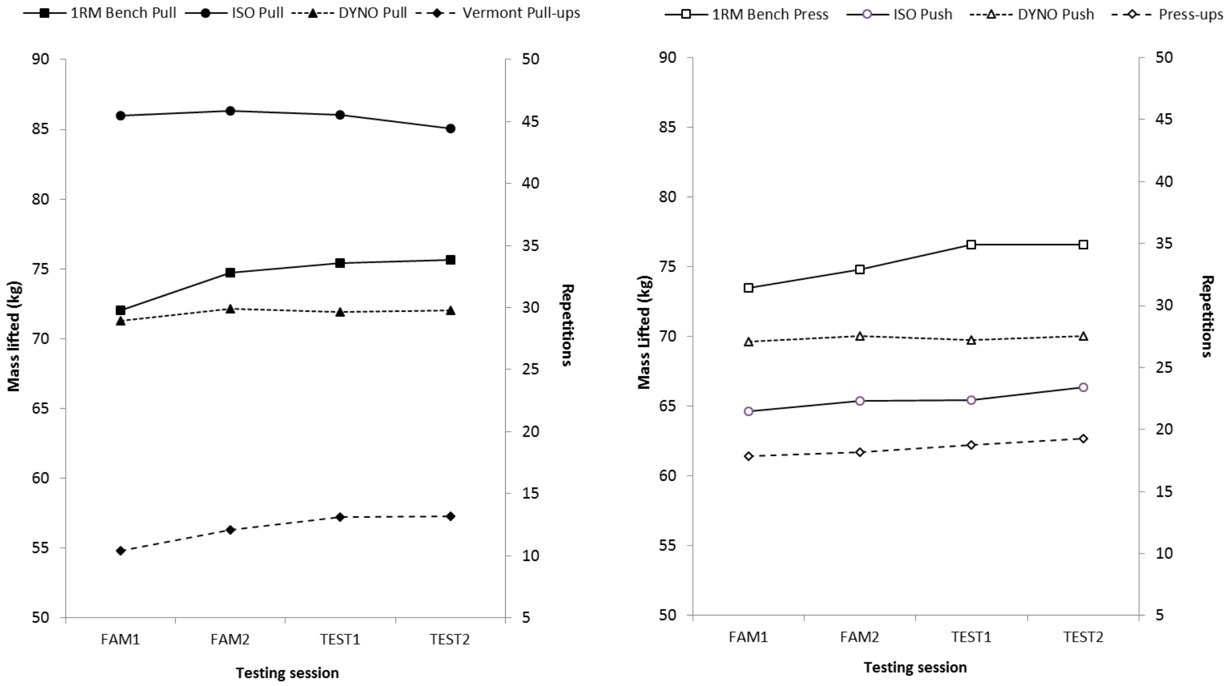

Figure 5.6 Strength scores between FAM and TEST sessions in all tests. Note: S.D. error bars removed for clarity in viewing, 1RM – one repetition maximum, ISO – Peak Isometric force, bodyweight tests scores (repetitions) are displayed on secondary axes

Reliability coefficient tests determined from the two main testing trials (TEST1 versus TEST2) suggested an excellent reliability between all upper body strength assessments with ICCs ranging from 0.988 to 0.999 (Table 5.1). The magnitude of the relationships between strength assessments to the gold standard 1RM assessments were found to be very large to nearly perfect (Table 5.2). Relationships between Press-ups and Supine pulls with rel1RM assessments were stronger than standard 1RMs and resulted in nearly perfect correlations ($r \geq 0.918$) though a similar strength relationship was observed between Press-ups and 1RM Bench Press ($r = 0.907/0.908$) (Table 5.2).

Table 5.1 Descriptive characteristics and reliability (ICC) from main testing sessions

Pull	TEST1	TEST2	ICC	95% range
1RM Bench Pull (kg)	75.4 ± 24.1	75.7 ± 24.8	.994	(.986 - .997)
rel1RM Bench Pull (kg/kg BM)	0.90 ± 0.22	0.96 ± 0.22	.989	(.976 - .995)
ISO-Pull (kg)	86.0 ± 29.5	85.1 ± 28.7	.998	(.995 - .999)
DYNO-Pull (kg)	71.9 ± 24.7	72.0 ± 24.8	.993	(.983 - .997)
Supine pulls (reps)	13.1 ± 9.6	13.2 ± 9.4	.994	(.987 - .997)

Push	TEST1	TEST2	ICC	95% range
1RM Bench Press (kg)	76.6 ± 32.4	76.6 ± 32.1	.999	(.997 - .999)
rel1RM Bench Press (kg/kg BM)	0.96 ± 0.33	0.96 ± 0.33	.998	(.995 - .999)
ISO-Push (kg)	65.4 ± 31.0	66.4 ± 31.8	.996	(.992 - .998)
Press-ups (reps)	18.8 ± 12.7	19.3 ± 13.0	.994	(.987 - .997)
DYNO-Push (kg)	69.8 ± 25.5	70.0 ± 24.3	.988	(.973 - .995)

Note: 1RM – one repetition maximum, ISO – Peak Isometric force

Interrelationships between strength assessments are presented with both testing sessions displayed in Table 5.2. TEST1 and TEST2 relationships between all testing methods resulted in correlations that were at least very strong (r ≥ 0.824), with 8 out of 12 considered nearly perfect (r > 0.90). When evaluating the relationship between bodyweight field tests and maximal strength assessments relative to body weight correlations between

Table 5.2 Pearson's Product Moment correlations (r) between maximal tests, TEST1 / TEST2 (all $P < 0.001$).

Pull	1RM Bench Pull	ISO-Pull	Supine pulls	*rel1RM Bench Pull*
1RM Bench Pull				***.890 / .899***
ISO-Pull	**.949 / .934**			
Supine pulls	**.855 / .831**	.848 / .835		*.926 / .918*
DYNO-Pull	**.970 / .977**	.924 / .922	.834 / .827	
Push	**1RM Bench Press**	**ISO-Push**	**Press-ups**	***rel1RM Bench Press***
1RM Bench				***.939 / .938***
ISO-Push	**.966 / .972**			
Press-up	**.907 / .908**	.905 / .904		*.955 / .956*
DYNO-Push	**.949 / .922**	.957 / .949	.883 / .839	

Note: Bold text indicates relationships with criterion 1RM tests, italics denote addition of rel1RM calculations), 1RM – one repetition maximum, ISO – Peak Isometric force.

5.4 Discussion

The aim of this study was to establish the reliability, validity and interrelationships of body strength assessments to assess the suitability of inclusion into the British Sailing Team's Olympic pathway physical testing battery. All of the upper body strength assessments used exhibited high levels of reliability (ICC = 0.988 to 0.999) and isometric and field testing tests were shown to be valid when correlated to the accepted gold standard 1RM tests (r = 0.918 to 0.977). All strength assessments revealed very strong to nearly perfect relationships (r =

0.824 to 0.977). Participants required between one and two familiarisation sessions before a plateau was observed in strength assessments (P > 0.056).

Tests of upper body strength used in the study have been shown to be very reliable across all methods as demonstrated by high ICCs > 0.988 (Table 5.1). This is in line with previous research in the range of tests as ICCs ranging from 0.96 – 0.99 were found in 1RM bench press and bench pull exercises (Bell *et al.*, 1993; Invergo *et al.*, 1991; Lawton *et al*., 2013; Levinger *et al.*, 2010; McGuigan *et al.*, 2010; McGuigan and Winchester, 2008). Upper body isometric PF assessments have previously revealed ICCs from 0.82 to 0.95 (Kilduff *et al*., 2002; Pryor *et al.*, 1994), Press-up and pull-up variations have also been shown to exhibit similarly high levels of reliability (ICC = 0.83 to 0.99) (Invergo *et al.*, 1991; Jackson *et al.*, 1994; Negrete *et al.*, 2010; Wood and Baumgartner, 2004). The only mention of reliability using the Concept DYNO is equivalent from the findings in this study (ICC 0.96 vs. 0.994 – 0.988) (Lawton *et al.*, 2013) although the protocols were distinctly different the direct comparison of the current findings with previous research is difficult when observing the range of protocols and techniques previously utilised.

It has been suggested that the level of previous resistance training experience may affect the reliability of maximal strength testing (Cronin and Henderson, 2004; Ritti-Dias *et al.*, 2011). When assessing the magnitude of learning effect in this study, a One-way repeated measures ANOVA revealed a plateau in performance between TEST1 and TEST2 (P > 0.065) revealing that two familiarisation sessions were required to achieve a reliable score. No difference in performance was recorded between the FAM2 and TEST1 in 1RM Bench Pull, both ISO- tests, Supine pulls and DYNO tests (P > 0.056) demonstrating that these tests only required one familiarisation session to ensure a reliable result. The sample in this study reported a minimum of six months resistance training experience which was less than the experienced group (greater than 24 months) in Ritti-Dias *et al.* (2011) study where a learning effect was completely absent during the four sessions. This may explain why the current participants required familiarisation sessions to achieve a reliable score, and was more in line with Cronin and Henderson's (2004) study whose participants were of an athletic background and required 2-3 sessions to accurately assess strength.

Previously the output of relationships between isometric PF and 1RM have been mixed, Haff *et al.* (2005) found near perfect correlations between MTP and bench press (r = 0.99) however, studies that investigated isometric and dynamic bench press movements found small to moderate relationships (r = 0.16 to 0.55) (Ignjatovic *et al.,* 2009; Murphy and Wilson, 1996). Possible explanations for these findings may be that Ignjatovic and colleagues (2009) did not report any familiarisation and participants performed isometric contractions at two different elbow angles to this study. Murphy and Wilson (1996) used similar elbow angles, but compared these to a seated medicine ball throw as the dynamic movement.

Similar to isometric PF assessments, field tests have shown varied relationships with 1RMs. This may be due to the range of assessments that have been investigated, and possibly that some of these studies used fixed-resistance machines e.g. chest press instead of a free-weight bench press (Levinger *et al.,* 2009). In line with Baumgartner and colleagues (2002) study, where a revised push-up technique was assessed for objectivity, reliability and validity, correlations of r = 0.80 to 0.87 were found when comparing bench press performance at a percentage of body weight, we made our 1RM scores relative to body mass in line with these findings which exhibited stronger relationships (r = 0.908 – 0.972). Our findings of Supine pulls correlation to 1RM also appears stronger than previously reported (Woods *et al.*, 1992). More research needs to be conducted in this area. Stronger relationships were observed between the Concept DYNO and 1RMs in this study compared to previous work (Lawton *et al.*, 2013), this is hypothesised to be due to using a different testing and calibration protocol.

When it comes to selecting the most appropriate method of strength assessment, the environment and sample should be considered as well as the sporting context (McMaster *et al*., 2014). It appears from the current study that due to the very strong reliability, validity and relationships between testing methods, that all tests have the potential to be used to assess strength in recreationally trained males and females. Table 5.3 highlights the pros and cons of each method. It is difficult to use the maximal strength and strength-endurance methods interchangeably as they arguably assess different aspects of strength, though 1RMs and isometric PF can be normalised which appears to enhance the relationship with weight-bearing field tests. It appears that the more direct the measurement of maximal strength, the more time-consuming and expensive it is. Therefore the need for direct measurement, versus the cost and time available will guide the testing selection. Elite sport pathways must be aware of the various negative psychological effects could result from obtaining zero values during field tests using bodyweight, especially in weaker sailors (Wood and Baumgartner, 2004). However the use of full Press-ups may be more beneficial as scores can be directly comparable between all athletes over time, and there are many important moments in activities and sports where males and females must manoeuvre their own body weight.

There is a need for acceptance in standardisation within tests that assess strength in research and in the applied setting to enable comparison between groups. If laboratory-based isometric PF assessments are used, either a standardised elbow angle should be advised or multiple attempts to find the joint angle for optimum force production, which arguably is closer to a value of maximum strength. 1RM testing should follow a set protocol (i.e. Earle, 1999), and bodyweight testing should follow set criteria across all populations. While considering the validity to the dynamic aspect of sports and exercise the 1RM should be regarded as the gold standard measure of maximal strength.

Table 5.3 Pros and cons of methods of strength assessment investigated in this study

	Time	Testers	Set-up	Measure	Muscle action	Pro's	Con's
1RM	20-25 min	2	1 min	Maximal strength	Dynamic	Gold standard, amount of research	Time, specialist equipment, no. of experimenters
ISO	3 min	1	10 min	Maximal strength	Isometric	Exact measure of maximal strength	Specialist equipment, time, validity of static contraction
BW	<1 min	1	<1 min	Strength - Endurance	Dynamic	Efficient, no equipment, able to practice technique safely on own	No standardised technique, not a measure of maximal strength, zero values
DYNO	<1 min	1	<1 min	Maximal strength	Dynamic	Efficient	Specialist equipment

Note: 1RM – 1 repetition maximum, ISO – Peak Isometric force, BW – Bodyweight

5.5 Practical applications

Supine pulls and Press-ups (Baumgartner *et al.*, 2002) have been reported to be reliable and valid measures of strength in a similarly trained group of males and females to elite pathway sailors after one to two familiarisation sessions. These tests are therefore recommended to be used in the British Sailing Team's Olympic pathway physical testing battery as measures of upper body strength. It is key for sailors to have the opportunity to practice these tests pre-profiling, to reduce the chance of error via learning effect.

The stimulation for this study was the need to find suitable upper body strength tests due to the manufacturing of Concept DYNO being discontinued, therefore the usefulness of this machine is void for the on-going purpose of assessing strength in Olympic pathway sailors. However the findings of this study report strong relationships with Supine pulls and Press-ups, therefore retrospective DYNO data may still be utilised to compare with current pathway sailors' strength data.

Chapter 6 Assessing the Usefulness of Methods of Predicting Peak Adult Height and estimating maturation in the Olympic Sailing pathway

6.1 Introduction

The previous chapter identified the long-term solution for the assessment of upper body strength within the British Sailing Team's Olympic pathway physical testing battery. This chapter investigates the importance of predicting peak adult height by investigating the accuracy and usefulness of two non-invasive methods, and based on that conclusion, the most suitable method for predicting peak adult height and to assess maturity to inform the physical testing battery.

The prediction of peak adult height (PAH) in children is commonplace in a paediatric endocrinology setting, especially when assessing unusual height characteristics relative to chronological age (CA) (Thodberg *et al.,* 2009), partially due to the potential of compromised psychological and physiological development (Khamis and Guo, 1993). Being able to accurately predict PAH in sport has potential application in the identification and development of talented athletes (Vaeyens *et al.,* 2009) aiding in selection and continuing support of developmental trajectories in particular sports and/or tactical positions (Ostojic, 2012; te Wierike *et al.,* 2015).

At senior elite level success has been linked to certain physical traits i.e. height. Due to this relationship it is now seen as standard to measure and monitor physical characteristics as part of a performance profile (Slater *et al.,* 2013). Malina (2011) is in agreement stating that PAH plays a major role in impacting success in some (but not all) sports through providing a natural advantage, based on the specific game demands. Sports that demonstrate a performance advantage of possessing tall height include: volleyball (Malousaris *et al.,* 2008; Pion *et al.,* 2015), badminton (Phomsoupha and Laffaye, 2015), rowing (Mikulic, 2008), basketball (Ziv and Lidor, 2009), Australian Rules Football (AFL) (Pyne *et al.,* 2006) and more specifically to this thesis, sailing (Bojsen-Möller *et al.*, 2007).

In volleyball possessing greater height has particular benefit due to the demands of players attempting to spike and block the ball over a net that separates the two courts (Pion *et al.,* 2015) measuring 2.43 m for males and 2.24 m for females. Height has been shown to distinguish performance level in Greek national leagues, as hitters, centres and setters participating in the highest A1 division were taller than the A2 counterparts (181.2 ± 4.5 vs. 173.4 ± 6.2 cm, 182.0 ± 4.6 vs. 178.7 ± 4.8 cm and 176.9 ± 4.1 vs. 170.9 ± 4.2 cm respectively) (Malousaris *et al.,* 2008). Pion *et al.* (2015) did not find that height differentiated performance level in female volleyball players, although this was due to the homogenous nature of the sample as athletes were all chosen from a Talent programme where a prerequisite of selection was a tall height as a key performance factor. Similar to volleyball, successful badminton players are generally regarded as tall and lean due to increasing the percentage of situations where attacking 'smash' shots can be performed over a net of fixed dimensions (Phomsoupha and Laffaye, 2015). Confirmation of this was reported by Poliszczuk and Mosakowska (2010) who analysed the heights of the top 13 world ranked players and found these players to be 5 cm taller than those of a lower level.

Height has been shown to be proportional to performance level in elite rowing, exhibited by a study of 54 Croatian national champions and members of the Olympic team (Mikulic, 2008). Elite senior rowers were found to be taller than sub-elite (194.0 ± 2.7 vs. 188.6 ± 5.4 cm respectively). Performance benefits of increased height are manifested in increased stroke length (Ingham *et al.,* 2002), and the mechanical advantage of increased leg length providing a greater drive phase (Claessens *et al.,* 2005). Basketball players generally possess a performance benefit of being taller due to providing a less obstructed position for shooting to a hoop 10ft above the ground (Ziv and Lidor, 2009). Players in the Top five teams vs. the bottom five teams in the female World Championships were reported to be taller but this was only significant in the guard position (173.7 ± 5.3 vs. 167.0 ± 5.3 cm respectively) (Carter *et al.,* 2005) potentially related to the difference in positional requirements within the team.

Within team sports, specific physical requirements are evident between different positions, this is particularly true in Australian Rules Football where within the yearly national draft anthropometrical and physical factors are key elements for selection (Pyne *et al.,* 2006). 495 national draft players were measured for height between 1999 and 2004, with a great variance found between players in different positions. Due to this discrepancy and the specific demands of key positions on the field the AFL game development team renamed positions referencing the height requirements e.g. taller forward, medium forward. Cohen effect sizes were calculated and revealed a large effect size (1.33 – 1.95) for height between the tall and medium positions selected for the draft (Pyne *et al.,* 2006) with taller positions also recording reduced sprint ability (0.23 – 0.57, small) and agility (0.64 – 1.11, moderate) than medium positions further highlighting the specific positional demands.

In Olympic sailing PAH is deemed important as athletes will aim to maximise righting moment to increase performance (boat speed) (Cunningham and Hale, 2007; Larsson *et al.,* 1996). To achieve this in a range of classes including double-handed boats there are varying specific boundaries for physical sizes that are successful (Bojsen-Möller *et al.*, 2014). Athlete and coach quotes from Chapter Three confirm the importance of height and physical size at senior elite level and also the range of sizes required in different boats. Leverage, i.e. the ability to use height to produce righting moment and therefore speed (Mackie *et al.,* 1999) was mentioned specifically:

"Everyone's fitness is fairly high [at Olympic level] you start to notice some of the physical differences. So you have someone who is 6ft 2 and someone who's 5ft 8 racing against each other, no matter how fit the short of person is they're always going to be giving away leverage - which turns into boat speed."

"If there was someone that was the same as me in every other way apart from they were taller, then they definitely would be better - Well they could make a boat go faster"

"As soon as you get to Olympic racing it [size] is non-negotiable – if you are not tall and fit you won't win races…. You have sailors that are really short that do well at about 50% of regattas, and then really averagely in the other half, so you need to be good in all conditions and exceptional in a couple."

"We weren't just inherently fast because we weren't the right size."

"The more leverage the better especially when the breeze is up."

With competitive sailing performance being weight dependent it is not surprising that there is a dearth of contemporary research published on the exact dimensions of the super-elite and elite athletes. The Finn (2009) and RS:X Men's and Women's fleets (2012) have published some individual and mean data online (International Finn Association, 2010; RS:X Class.com, 2012). There is a small amount of sub-elite and Youth data available (Callewaert *et al.,* 2014b; Verdon *et al.,* 2012) alongside the self-reported athlete Olympic data feeds (ODF) generated from London 2012 and Rio 2016 Olympics (Figure 6.1) (The Guardian, 2012; Olympic.org, n.d.).

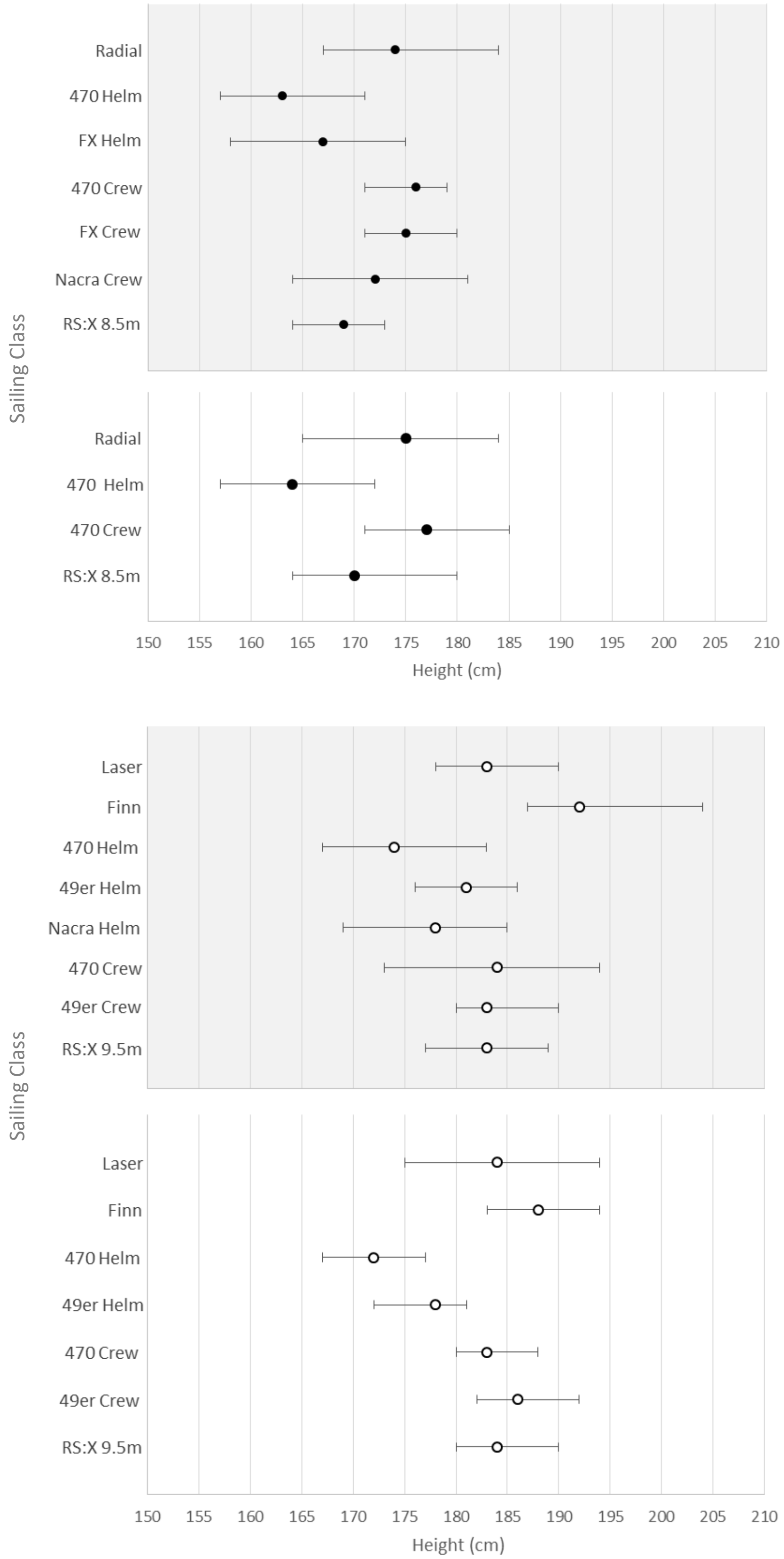

Figure 6.1 Self-reported mean heights of female (filled icons) and male (empty icons) Olympic Class sailors who finished in Top ten in Olympic Games in Rio 2016 (shaded) and London 2012 (white background) in classes sailed in the Rio 2016 Olympics. Error bars display +/- one S.D. from the mean.

Data presented from the International Finn Class Association census in 2009 (International Finn Association, 2010) shows sailors that are ranked in the top 15 in the world are almost identical in height to the top 50 ranked (188.9 ± 4.73 cm vs. 188.8 ± 4.46 cm). A quote from Czech Finn sailor Tomas Vika provides insight into the particular nature of the fleet:

"The most important thing is that there is no other Olympic dinghy class for guys like me who weigh more than 85 kg. The Finn is called the 'heavyweight' dinghy, but it's not so simple: If you are more than 180 cm tall and you want to work on your physical condition in a gym you will always weigh more than 85 kg."

In the RS:X fleet over 2011 and 2012 Carmen Vaz, an ex-MOD sailor, conducted an anthropometric survey of the top 63 male and 62 female sailors who participated in the class's world championships. Top 15-ranked sailors in the RS:X men's fleet average heights were 183.6 and 185.2 cm at Cadiz and Perth world championships respectively, however the average across the top 63 was lower at 181.2 cm. The difference between the lower-level performers who competed in the second tiered 'silver' fleet were even shorter at 178.7 cm. Female RS:X top 15-ranked sailors' average height were 171.4 and 170.7 cm, compared to 168.9 cm across the top 62. It should be also noted that the average of the top ten female RS:X sailors in Cadiz were taller, measured at 172.9 cm leading the researcher to conclude that top performers in the male and female RS:X fleets are taller. Unfortunately no further statistical analysis was performed such as standard deviation or minimum and maximum ranges. Vaz also measured body mass, sum of seven skinfolds and armspan, adding to the findings that top level RS:X sailors in both sexes were leaner (lower % body fat) and had greater armspan. Elite data collected through measurement (International Finn Association, 2010; RS:X Class.com, 2012) and self-reported from the Olympic Data Feed in the Finn and RS:X classes are displayed in Table 6.1 and Table 6.2.

Table 6.1 Comparison of heights recorded for the Olympic men's Finn class

Class	Finn Census (2009)	ODF Medal race (London 2012 / Rio 2016)
Finn	Top 15 – mean 188.9 ± 4.73 cm	2012 – mean 188 cm (range 183 – 194 cm)
	Top 50 – mean 188.8 ± 4.46 cm	2016 – mean 192 cm (range 187 – 204 cm)

Table 6.2 Comparison of heights recorded for the Olympic women's and men's RS:X class

Class	Vas (2011/2012)	ODF Medal race (London 2012 / Rio 2016)
RS:X Women	Top 10 – mean 172.9 cm Top 15 – mean 171.4 and 170.7 cm Top 62 – mean 168.9 cm	2012 = mean 170 cm (range 164 – 173 cm) 2016 = mean 169 cm (range 164 – 173 cm)
RS:X Men	Top 15 – mean 183.6 and 185.2 cm Top 63 – mean 181.2 cm Silver fleet – mean 178.7 cm	2012 – mean 184 cm (range 180 – 190 cm) 2016 – mean 183 cm (range 177 – 189 cm)

At Youth level elite Laser Radial sailors were found to be taller than Optimist sailors (176.3 ± 4.8 vs. 157.1 ± 8.7 cm respectively), which represents the increased requirement of righting moment to counterbalance a greater sail area (Callewaert *et al.,* 2014b). No differences were found between elite and non-elite Laser Radial sailors (0.3 cm) although elite Optimist sailors were on average 10.6 cm taller.

When considering the most suitable method for predicting PAH, it has been proposed that an indicator of maturation status must be included (Sherar *et al.,* 2005). Currently it is accepted that the gold standard method of maturation status assessment is the measurement of skeletal age (SA) (Lloyd *et al.,* 2014). A number of prediction methods exist using SA with various procedures and levels of accuracy (Bayley and Pinneau, 1952; Roche *et al.,* 1975; Tanner *et al.,* 1975; Tanner *et al.,* 1983; Tanner *et al.,* 2001). The Bayley-Pinneau (BP) method (Bayley and Pinneau, 1952) has been revised for use with the Greulich-Pyle (1959) atlas measurement of the hand and wrist as an estimate of SA, combined this with current chronological age (CA) and height. The prediction tables created place children into categories based on CA versus SA being more or less than one year. Accuracy of this method exhibits median error of approximately ± 4 cm (Bayley and Pinneau, 1952) from 7 to 18.5 years in males and six to 18 years in females. Another prediction method that utilises the Greulich-Pyle (1959) atlas measurement is the Roche, Wainer and Thissen (RWT) method (Roche *et al.,* 1975). Predictions are made using regression equations using CA, recumbent length, body mass and mid-parental height alongside SA. The RWT method is considered only usable in males and females up to 16 and 14 years respectively, and with less than 50% of the bones in the hand and wrist are considered adult. Median errors of the RWT method are approximately 2.5 to 3 cm (Roche *et al*, 1975). There have been three developments of the Tanner-Whitehouse (TW) method of predicting PAH (Tanner *et al.,* 1975; Tanner *et al.,* 1983; Tanner *et al.,* 2001) named TW1, TW2 and TW3. These methods use the Tanner-Whitehouse SA assessment of hand and wrist, with a number of different measurements including CA, height, skeletal maturity score (SMS) of radius, ulna and short ones (RUS) plus the change in height/SA over the previous year. This method has reported median errors of 3-7 cm, with accuracy increasing with CA in boys and girls over 13-14 years old which can be corrected using mid-parental height (Tanner *et al.,* 1975).

Prediction methods of studies highlighted in the previous paragraph utilising estimates of SA have been shown to have acceptable levels of accuracy, with the majority revealing median error of equal to 4 cm or less across a range of childhood CA. However these methods have limitations in that the measurement of SA using radiographs of the hand and wrist expose children (and measurers) with radiation, error may exist in the accuracy of the analysis of the radiographs (inter-rater difference 0.17 ± 0.2 years, N = 18, Roche *et al.,* 1983) and incur high financial and resource costs (Sherar *et al.,* 2005). Due to these reasons methods that predict PAH without the use of SA have been considered, in some cases exhibiting similar level of prediction accuracy (Beunen *et al.,* 1997; Khamis and Roche, 1995; Sherar *et al.,* 2005; Wainer *et al.,* 1978).

Methods that predict PAH without the use of SA have been created, including the Beunen-Malina (BM) method (Beunen *et al.,* 1997) which was validated against the Leuven Growth study in 102 males ranging from 13 to 18 years old includes measurement of CA, height, sitting height and subscapular and triceps skinfolds. This method tended to underestimate PAH with median error of -0.3 to -0.6 cm, although the variance of 25^{th} to 75^{th} and 5^{th} to 95^{th} percentiles ranged from -3.4 to 2.8 cm and -7.3 to 6.2 cm respectively. This may appear less accurate than SA methods however, the same growth data had simultaneous SA assessment recorded, and TW2 method revealed median error of -0.03 to 2.9 cm, with the same value percentiles ranging from -1.5 to 5.6 cm and -4.2 to 7.3 cm respectively, exhibiting similar levels of accuracy (Beunen *et al.,* 1997).

Sherar *et al.* (2005) moved away from linear models of PAH prediction and utilised cumulative height velocity curves in combination with assessment of somatic maturity (PHV) using the calculations of Mirwald *et al.* (2002). The prediction of PAH required accurate measurement of CA, height, sitting height and body mass which provided an estimate for PHV which enabled children to be classified as early-, middle- or late-maturers. From this data it was possible to predict how much more a child has to grow (see Appendix 3), which was then added to current height. The prediction error (95% CI) of this method was reported to be ± 5.35 cm in males and ± 6.81 cm in females, though it was stated that the equation was only accurate between girls aged 8 to 16 and boys aged 9 to 18 years (Sherar *et al.,* 2005).

Adult height has been understood to be mostly dependent on hereditary factors when in favourable conditions for growth, i.e. parental height. It must be acknowledged that these are compounded by epigenetic and environmental factors (Tanner *et al.,* 2001). Khamis and Roche (1995) developed an equation to predict PAH using mid-parental height alongside measurements of CA, height and body mass using participants from the Fels Longitudinal study based in South West Ohio, USA. This sample comprised of 223 males and 210 females up to 18 years old measured every six months from 3 years old. Although this method does not have a measurement of biological maturity, the average 90% error boundaries are ± 5.3 cm for males and ± 4.32 cm for females (Khamis and Roche, 1995). The 90% errors were approximately 2.5 cm and 0.25 cm more accurate for males and females than the Wainer *et al.* (1978) equation in which SA was substituted with CA using the RWT method. In accordance with the method of Sherar *et al.* (2005) accuracy of the prediction is based on the skill of the measurers, the period of least accuracy is at approximately 14 years in boys and 12 years in girls when compared to RWT as this is where SA has the most impact of prediction (Khamis and Guo, 1993).

Any method of predicting PAH will ultimately incur a degree of error, predominantly due to the individual variation in the tempo and timing of growth, especially around typical periods of accelerated growth. Limitations of all methods, regardless of inclusion of SA, include the lack of data on different ethnic populations and children with growth-related disease (Beunen *et al.*, 1997; Khamis and Roche, 1974; Sherar *et al.*, 2005). Another practical use of employing the non-invasive prediction methods in the chapter is to assess maturity, as both methods use estimates of maturity timing within the prediction either related to APHV (Sherar *et al.,* 2007) or percentage of PAH (%PAH) (Khamis and Roche, 1995). Giving greater context of a sailor's current level of maturity may improve awareness of individuality and take into account the non-linear trajectory of development to benchmark current performance (Bergeron *et al.,* 2015) and design a safe and effective physical programme (Lloyd and Oliver, 2012).

Norton *et al.* (1996) discuss the term 'morphological optimisation', where distinctive anthropometry is found in athletes at the top elite level of particular sports due to the adaptation to specific training and competitive demands over time. Key to understanding whether this phenomenon exists in a particular sport involves obtaining data of super-elite athletes who are successful, then assessing the central tendency (mean) and spread (variance and/or range). It is accepted that sample sizes will be small for super-elite performers, although a small range of values at this level will indicate a close link of anthropometrical factors to performance, meaning that athletes outside of this range will find it very difficult/impossible to succeed. To be able to accurately predict PAH in the Olympic pathway is important, firstly this may aid sailors with decisions on expected trajectory and ultimate class and/or position choice in sailing when fully grown.

It appears that particular anthropometrical sizes are evident in different classes of sailing along the Olympic pathway including the Olympic level from the Finn (2009), RS:X (2012) and self-reported Olympic data, due to the variation of physical demand from the requirement to produce righting moment to balance the force of different sail and boat dimensions/weights (Callewaert *et al.*, 2014b; Castagna *et al.,* 2007; Mackie and Legg, 1999). There are a great deal of assumptions in coaches of what sizes are required of successful performance due to a lack of reliable super-elite data to confirm the central tendency and range. Therefore it is important to understand the anthropometrical requirements of successful Olympic sailing, but also to be aware of the range of prediction accuracy to aid the Olympic pathway maintain a constant flow of talented athletes with the physical attributes to support continuous success at Olympic level.

The aims of the study are as follows:

1) Compare the agreement and accuracy of two PAH prediction methods (Khamis and Roche, 1995; Sherar *et al.,* 2005) from retrospective data collection with measured PAH.

2) Describe how the level of agreement and accuracy of the two methods of PAH prediction are affected by chronological age and gender.

3) Understand how the range of accuracy of two methods of PAH prediction (Khamis and Roche, 1995; Sherar *et al.,* 2005) correspond with the current understanding of the ranges of height to be successful at super-elite level.

4) Based on the above aims to select a method to predict PAH and assess biological maturity within the British Sailing Team's Olympic pathway physical testing battery.

6.2 Methods

6.2.1 Participants

97 elite Junior and Youth sailors participated in this study (female *n* = 37, male *n* = 60). For inclusion in the study participants were members of the British Sailing Team's Youth pathway, were of white UK Caucasian decent, and were free from any known injury at the date of both measurements, which was confirmed by completion of a medical questionnaire. Participants provided their informed consent following written or verbal explanation of the procedures and potential risks of the study. Approval for this study was granted by the University of Chichester Research Ethics Committee.

6.2.2 Procedures

The procedures required to collect the data to answer the aims of the study were completed chronologically in a three-stage process described as follows:

Stage One – Retrospective anthropometric data collection

During physical profiling sessions for the British Sailing Team's Junior and Youth programme between 2003 to 2013 data was collected, which included CA, height, sitting height and body mass. For more detailed description of anthropometrical procedures please refer to section 4.2. This data was recorded by three physiologists working for the British Sailing Team, including the lead researcher of this thesis. All physiologists were level one anthropometrists accredited by ISAK, as part of holding this accreditation inter- and intra-rater reliability must be within set parameters. Relative technical error of measurement (TEM) of height, sitting height and body mass must be within 1.5% (intra-rater) during repeated measurements with at least 20 participants, and within 2% (inter-rater) of measurement of a level four anthropometrist (qualified through extensive experience in anthropometric measuring over a period of years, having publications in anthropometry and verified as intra-rater error of <1% by a criterion anthropometrist).

Stage Two – Measurement of actual PAH and predictions of PAH

Sailors who were measured during retrospective data collection were contacted as long as they made the criteria for actual PAH, classified by aged >21 years, or >19 years with two or more measurements with no further increase in height. Sailors were measured by the lead researcher (TEM % as follows: 0.05% height and sitting height, 0.08% body mass). All height measurements were conducted in the morning as per retrospective data collection. During measurement of actual PAH, sailors were asked to collect an estimate of maximum height achieved from each of their biological parents. Two PAH prediction methods were applied to the anthropometric data collected in stage one and two (Khamis and Roche, 1995; Sherar *et al.,* 2005) to compare agreement and accuracy with actual PAH measured. These methods are described below:

Sherar *et al.* (2005) applied gender-specific cumulative height velocity curves based on participant's maturity offset as calculated by Mirwald *et al.* (2002) to predict PAH. Years from PHV was calculated by applying a cubic spline to the velocity between age-points. Maturation status, i.e. whether an individual was an early-, average- or late maturer was predicted using the maturation offset in years from APHV using an algorithm based on the Saskatchewan Growth and Development study (SGDS) and Leuven Longitudinal Twin study (LLTS) (Mirwald *et al.,* 2002) (6) [$R = 0.94$, $R^2 = 0.89$, and $s_x = 0.59$]:

$$\text{Maturity offset (years)} = -9.236 + (0.0002708 \times (\text{Leg Length} \times \text{Sitting Height})) + (-0.001663 \times (\text{Age} \times \text{Leg Length})) + (0.007216 \times (\text{Age} \times \text{Sitting Height})) + (0.02292 \times (\text{Weight/Height} \times 100)) \quad (6)$$

Biological age groups were created using one year age groups with -0.5 to 0.5 years relative to APHV representing average maturers. Classification of maturity timing was created relative to PHV in the LLTS, to previously accepted norms for PHV of 12 years for girls and 14 years for boys (Malina *et al.*, 2004), with early maturers reaching PHV >1 year in advance, average within ± 1 year and late maturers >1 year after (Mirwald *et al.,* 2002).

Mean cumulative velocity curves were created for each maturity status for intervals of 0.1 year that were then used to calculate area under the curve. Maturity offset predicted calculated from years ± APHV and current age/height for each child was used with the estimated height left to grow, added from the individually created velocity curve table to calculate PAH (Appendix 3). Sherar and colleagues (2005) assessed the accuracy of the cumulative velocity curves by predicting adult height of a random selection of children from the LLTS and comparing against measured PAH. Accuracy of this method was found to be ± 6.81 cm in girls and 5.35 cm in boys 95% of the time (Sherar *et al.,* 2005).

The second PAH prediction method (Khamis and Roche, 1995) used in this study involved the collection of non-invasive measures of CA, height and body mass of the sailor plus mid-parental height. Mid-parental height was recorded via self-reporting, to allow for overestimation of self-reported height the Epstein adjustment equation was applied (7). This equation was constructed to adjust self-reported heights of males and females, using over 1,000 participants who on arrival to participate estimated their height and were then measured immediately after. Correlation coefficients for males and females were found to be nearly perfect (males: r = 0.95, females: r = 0.98):

$$\text{Males: adjusted height} = 2.316 + (0.955 \times \text{self-reported height})$$
$$\text{Females: adjusted height} = 2.803 + (0.953 \times \text{self-reported height}) \quad (7)$$

Using the method employed by the modified RWT (Roche *et al.,* 1975) with the variables collected produced a regression equation (8) that was applied to the data from the Fels Longitudinal study to predict PAH in age groups of 0.5 years (for calculation tables see Appendix 4). The accuracy of this method was proposed as ± 5.33 cm for males and ± 4.32 cm for females 90% of the time, which was only marginally less accurate than RWT equation that required SA assessment (Khamis and Roche, 1995). PAH equation presented (8) β_0 - intercept, β_{1-3} – coefficients to multiply with height, bodymass and mid-parent height:

$$Predicted\ PAH = \beta_0 + \beta_1 \cdot height + \beta_2 \cdot bodymass + \beta_3 \cdot mid\text{-}parent\ height \quad (8)$$

Stage Three – Estimates of ideal heights for successful sailors at super-elite level in Olympic sailing classes

Due to the dearth of measured height data in Olympic sailing, ideal heights for successful super-elite sailors were estimated by the top two coaches in all classes sailed in the Rio Olympic Games in 2016. Within the group of coaches questioned, at least one was the Olympic coach in Rio. The data was collected via face to face or telephone discussions. Coaches were asked whether an ideal height existed in the Olympic class that they coached in, whether there was a range of ideal height and if there was a broader range including minimum and maximum heights where sailors would remain competitive. Although it was pointed out in multiple discussions that if a sailor fell outside of the ideal height range, they would have to be exceptional relative to the super-elite fleet in other areas of performance, for example tactics, strategy or decision-making. All coaches that participated were happy with the ranges that were discussed, the data presented includes averages of ideal heights, and ranges displayed are the extremes of the combination of class coach discussion i.e. the lowest minimum, and highest maximum value reported.

6.2.3 Data Analysis

To determine the bias and limits of agreement between methods to predict PAH and measured actual PAH, Bland–Altman plots (Bland and Altman, 1986) were created by examining the difference between predicted and actual PAH (displayed on y-axis) against the mean of predicted and actual PAH (displayed on x-axis). 95% confidence intervals (CI) are displayed on the graphs as dashed lines, 50% CI were also calculated and reported in results section.

For analysis of agreement and accuracy between PAH prediction methods against actual PAH, sailors were split into male and female groups of yearly intervals (for sample sizes in each age group see Figure 6.4 and Figure 6.5). The yearly age groups were set from 11.5 to 17.5 years inclusive due to the minimum age of sailors in Junior programme and the maximum age limit of the prediction method of Khamis and Roche (1995) being 17.5 years. Up to five measurements were recorded for sailors during 2003 – 2013 time period, with only one measurement per year age group allowed. If a sailor had multiple measurements within an age group, the measurement closest to the mid-point of the year was taken i.e. closest to 13.0 years in the 12.5 to 13.5 years age group.

6.3 Results

The level of agreement between the PAH prediction methods of Sherar *et al.* (2005) and Khamis and Roche (1995) versus actual measured PAH in females and males appeared similar, as can be seen from the Bland-Altman plots (Figure 6.2 and Figure 6.3). For both methods the majority of predictions fall inside the 95% CI, which indicates that another athlete from the Olympic pathway's predicted height would fall between these limits of agreement with approximately 95% probability. Both prediction methods appear generally to under-predict PAH, when analysing mean bias and CIs the PAH prediction method of Khamis and Roche (1995) displayed slightly better accuracy and agreement against measured PAH with an improved bias of approximately 0.5 cm and narrower CIs of up to 0.87 cm in males at 95% (Table 6.3).

Table 6.3 Female and male mean bias and 50%/95% CI for PAH prediction methods of Sherar *et al.* (2005) and Khamis and Roche (1995)

Gender	Prediction method	Bias	50% CI	95% CI
Female	Sherar *et al.* (2005)	-0.92	1.96	5.65
	Khamis and Roche (1995)	-0.40	1.93	5.56
Male	Sherar *et al.* (2005)	-2.42	3.19	9.20
	Khamis and Roche (1995)	-1.95	2.89	8.34

In female sailors both PAH predictions displayed clearly greater agreement (evidenced through a narrowing of 95% CI dashed lines) as chronological age increased towards 17.5 years, however this was not observed in the males, in which a slight reduction was observed (Figure 6.2 and Figure 6.3). This trend was similar in the accuracy of both PAH prediction methods (Figure 6.4 and Figure 6.5). During further analysis of the male 16.5 – 17.5 years group, it was found that three participants increased in measured height from between 5.3 and 10.2 cm post-17.5 years. The PAH prediction equations of both Sherar *et al.* (2005) and Khamis and Roche (1995) estimate PAH to occur at 18 years in accordance with the measurement of PAH in the LLTS and Fels Longitudinal Study respectively. Therefore additional growth post-18 years may reduce the agreement and accuracy between prediction methods and measured PAH. To display the effect of the effect three male sailors who grew 5.3 to 10.2 cm post 16.5 to 17.5 years group, further Bland-Altman calculations were completed with the three male sailors removed, bias ± 95% CI reduced from -1.48 ± 6.43 to -1.48 ± 2.79 cm using Sherar *et al.* (2005), and -2.40 ± 7.22 to -2.40 ± 2.39 cm using Khamis and Roche (1995).

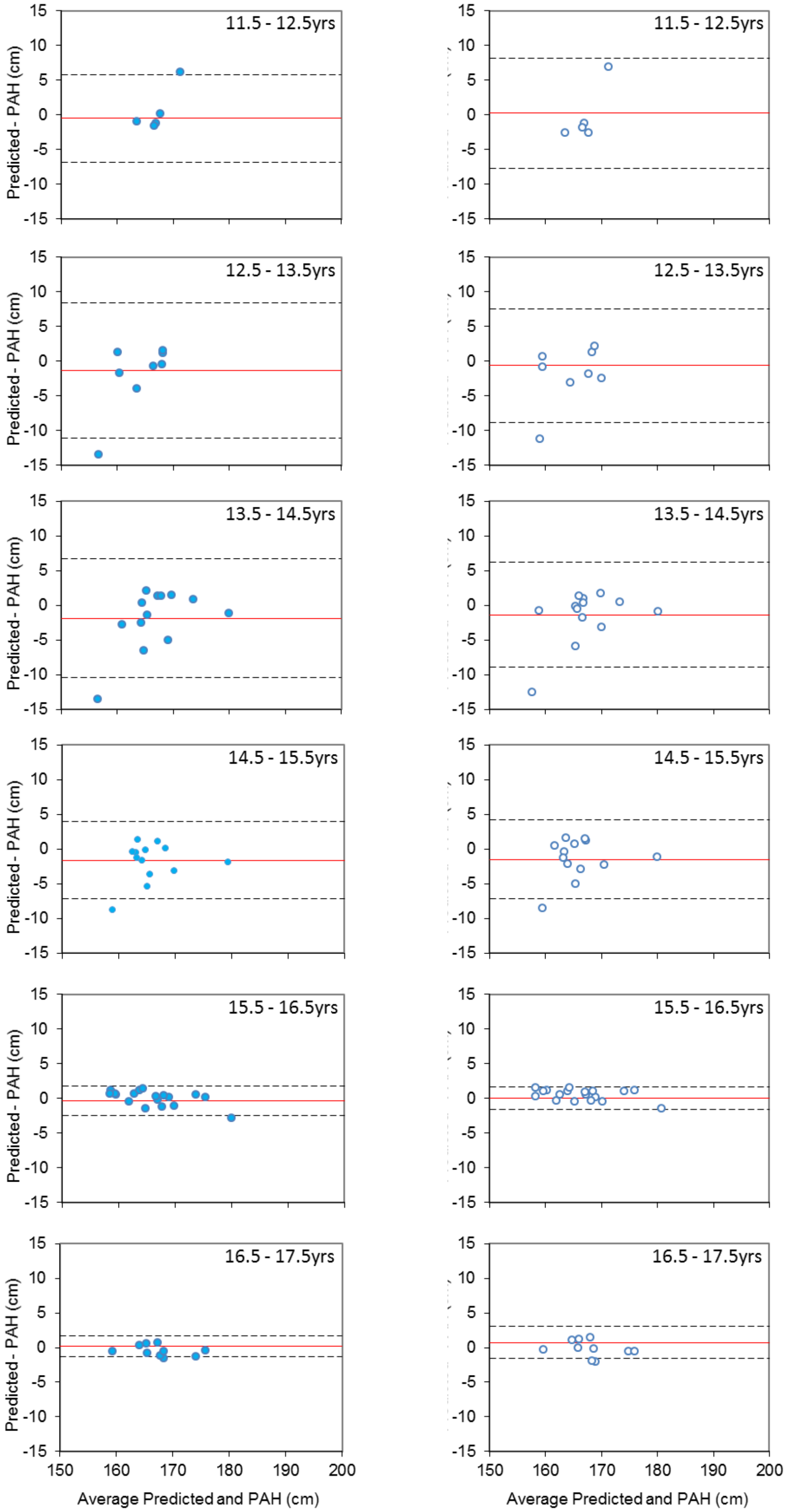

Figure 6.2 Bland-Altman plots for female sailors aged 11.5 – 17.5 years. Note: Red line = mean bias, dotted lines = 95% CIs, filled circles = Sherar *et al.* (2005), outlined circles = Khamis and Roche (1995)

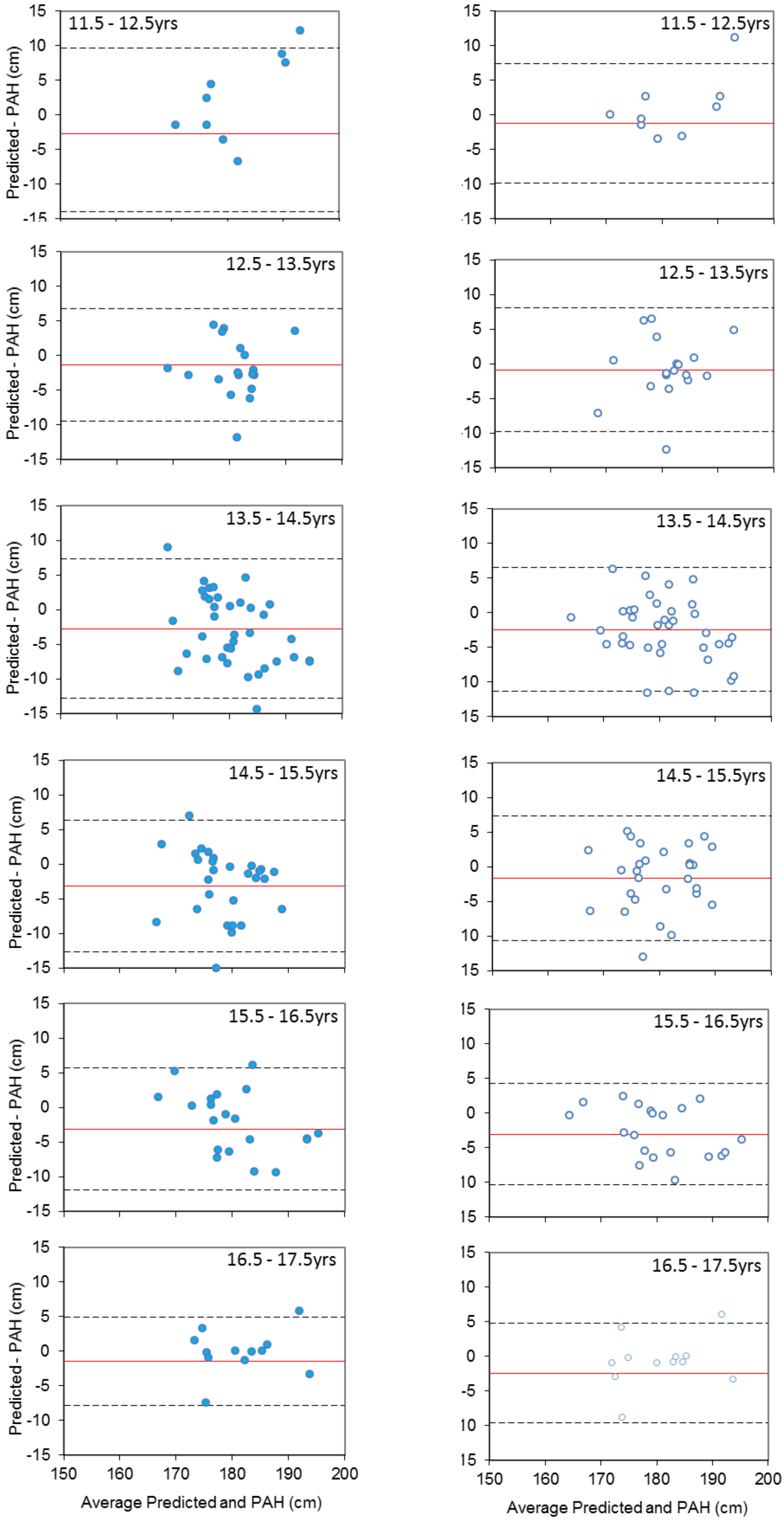

Figure 6.3 Bland-Altman plots for male sailors aged 11.5 – 17.5 years. Note: Red line = mean bias, dotted lines = 95% CIs, filled circles = Sherar *et al.* (2005), outlined circles = Khamis and Roche (1995)

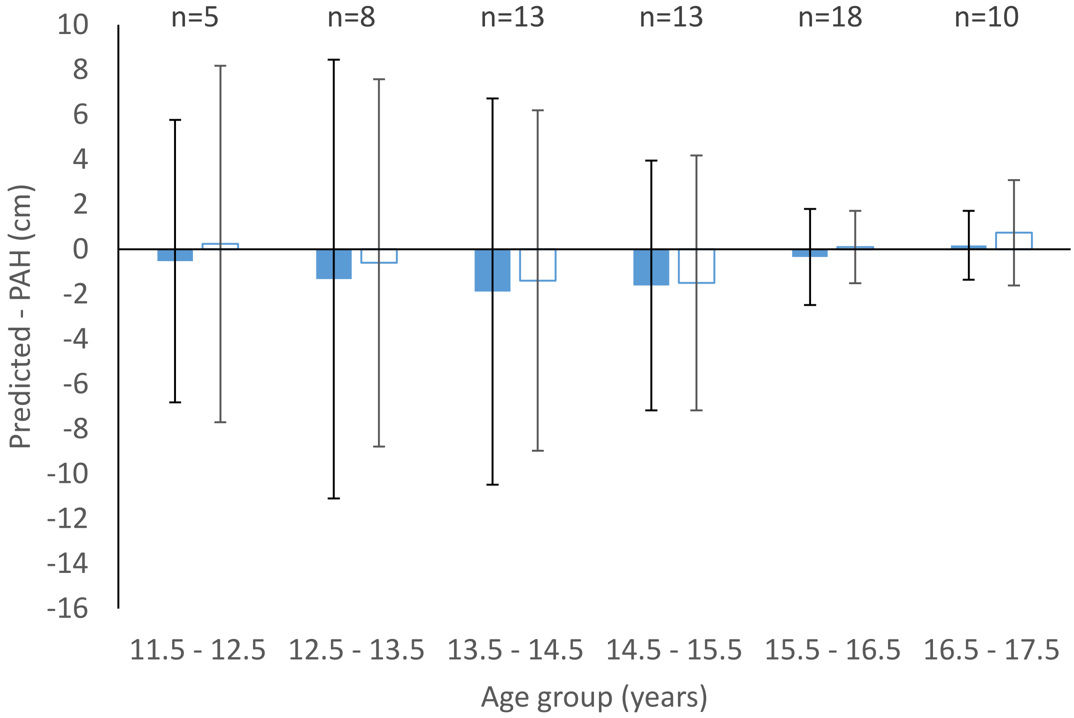

Figure 6.4 Accuracy of PAH predictions for female sailors according to chronological age groups. Note: Filled bars = Sherar *et al.* (2005), Outlined bars = Khamis and Roche (1995), Error bars denote 95% CIs

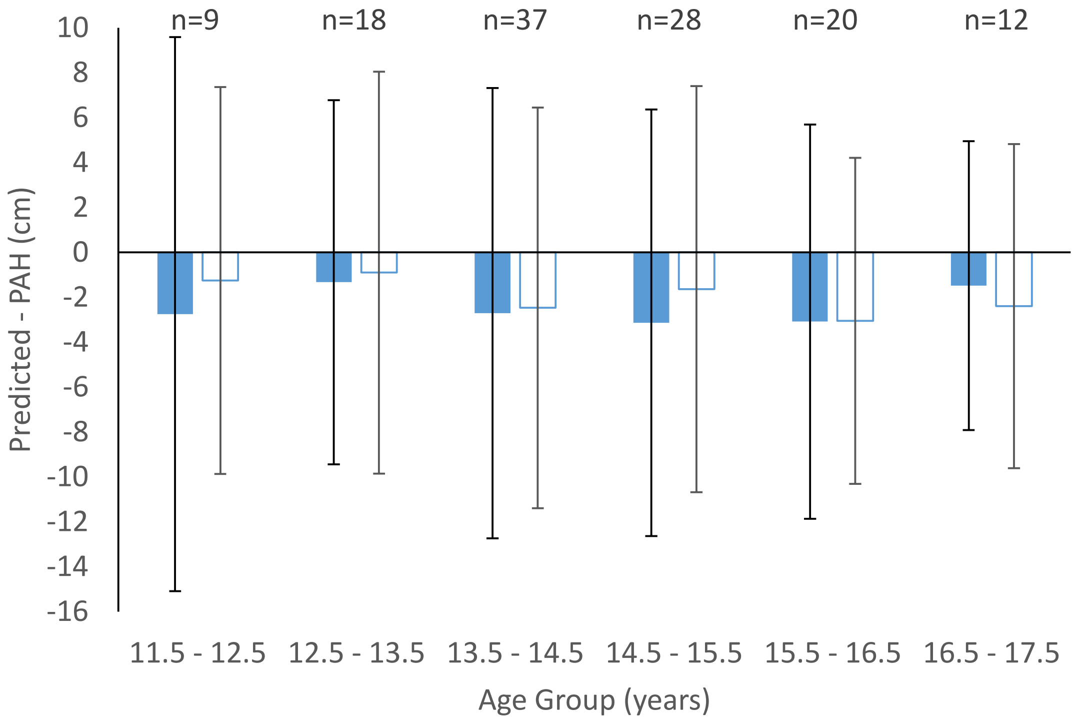

Figure 6.5 Accuracy of PAH predictions for male sailors according to chronological age groups. Note: Filled bars = Sherar *et al.* (2005), Outlined bars = Khamis and Roche (1995), Error bars denote 95% CIs

Ideal heights for successful super-elite sailors

The range of heights estimated to be successful at the super-elite level in female and male Olympic classes by the top two coaches in each Olympic class are displayed in Figure 6.6. Variation exists in the ideal height ranges across the different Olympic classes, overlap is displayed in the majority of classes between 175 and 185 cm in females and 180 and 190 cm in males. Both female and male classes reveal clear differences at either end of the spectrum when comparing the 470 helmsperson against all other classes except the RS:X in the females, with clear difference only observed with the Finn class in males.

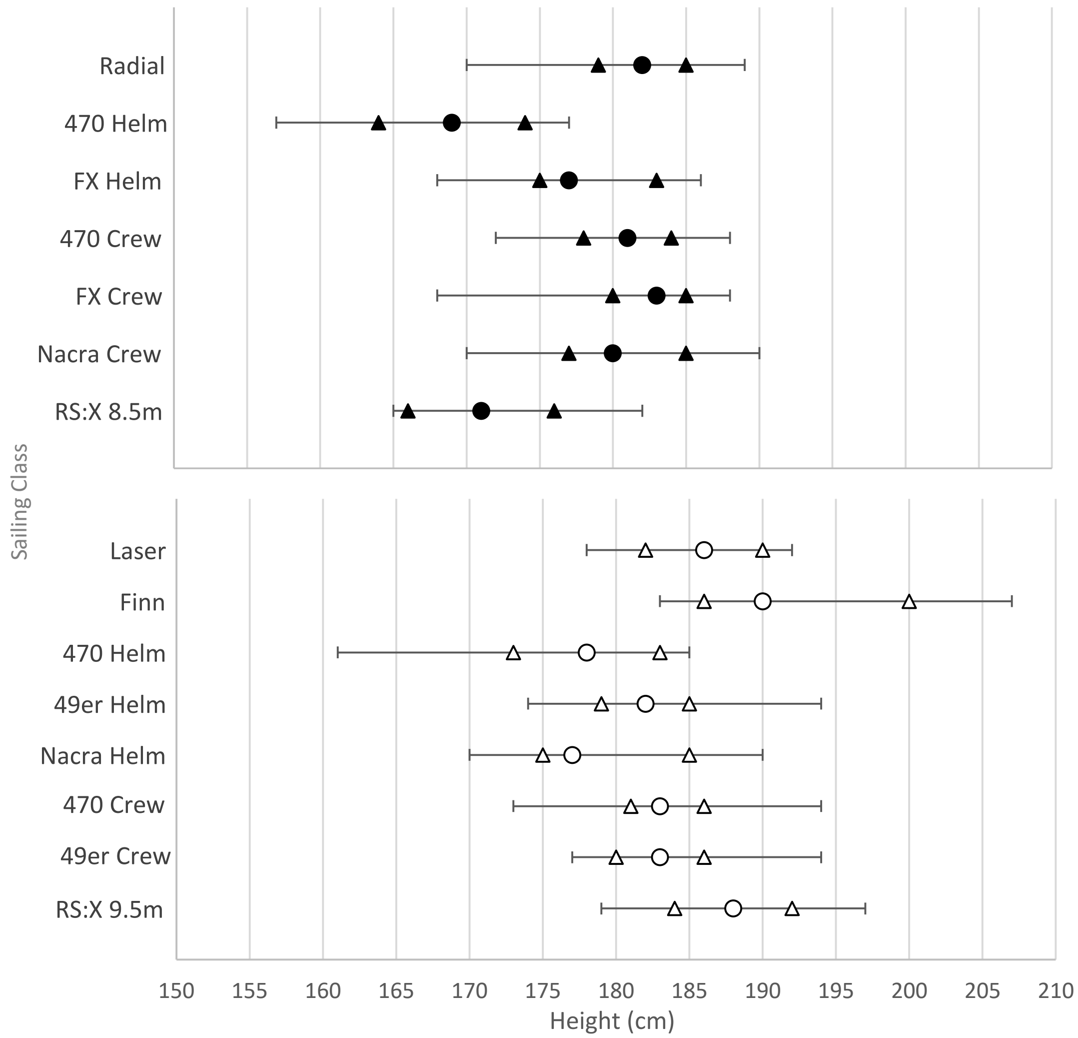

Figure 6.6 Mean estimates of height ranges for Rio 2016 Olympic classes from top two British Sailing Team coaches from each class. Note: • – female, o – male, circles - ideal height, triangles - range for ideal height, error bars – competitive range

6.4 Discussion

The aims of this study were to compare the agreement and accuracy of two PAH prediction methods (Khamis and Roche, 1995; Sherar *et al.,* 2005), describing whether there was an interaction of age or gender, and how the range of accuracy corresponded to the estimated ranges of height related to success at the super-elite level in Olympic sailing. With the aim of selecting the preferred method to predict PAH and estimate maturation status to add to the British Sailing Team's Olympic pathway physical testing battery.

Agreement and accuracy of PAH prediction methods

The level of agreement compared across both PAH prediction methods was similar, denoted by the spread of data points in the Bland-Altman plots (Figure 6.2 and Figure 6.3) in female and male sailors. In both sets of calculations almost all the predictions were within the 95% CI which indicates a good level of agreement against measured PAH. It was found that both methods tended to under-predict height, with the Khamis and Roche (1995) method displaying slightly better accuracy compared to the method of Sherar *et al.* (2005) (Bias ± 50%/95% CI: -0.4 ± 1.93/5.56 cm vs. -0.92 ± 1.96/5.65 cm in females and -1.95 ± 2.89/8.34 cm vs. -2.42 ± 3.19/9.20 cm). Sherar and colleagues (2005) presented 95% error ranges of ± 6.81 cm in females and ± 5.35 cm in males, displaying greater accuracy in female sailors in this study, however in males the accuracy was poorer compared to their previous findings. A similar outcome was observed in the accuracy of the Khamis and Roche (1995) method in this study as the original paper calculated the 90% error range at ± 4.32 cm for females and ± 5.33 cm for males compared to the 95% CI of ± 5.56 and ± 8.34 cm respectively.

Interaction of age and gender on PAH

A difference was observed in the trajectory of agreement between both PAH predictions as chronological age increased in females, but not in males. In females, as would be expected, the closer in age to PAH, the greater the agreement between predicted and actual PAH was observed (denoted by a narrowing of dotted lines on Bland-Altman plots (Figure 6.2 and Figure 6.3). This pattern was also reflected in accuracy (Figure 6.4 and Figure 6.5).

As described earlier there was less agreement and an under-prediction in accuracy of PAH predictions in male sailors. An explanation of this in males and to a lesser extent in females may lie in the height that is potentially left to grow past 18 years of age. Both prediction methods used 18 years as the classification for PAH based on previous longitudinal research studies (LLTS and Fels Longitudinal studies). It has been reported that post-18 years of age males and females continue to grow with median increases of approximately 1 cm in males and 0.6 cm in females, with greater increases for later-maturers (Khamis and Guo, 1993; Khamis and Roche, 1995). In this study three males out of the 12 in the 16.5 – 17.5 years age group still had 5.3 to 10.2 cm of growth left. To reveal the effect of this on this select age group further analysis was completed with the three male sailors removed, bias ± 95% CI reduced from -1.48 ± 6.43 to -1.48 ± 2.79 cm using Sherar *et al.* (2005), and -2.40 ± 7.22 to -2.40 ± 2.39 cm using Khamis and Roche (1995). Considering the small sample of this age group (n = 12) it is clear that these sailors who have grown a large amount after 17.5 years have a large impact of the accuracy of the equation. It is the intention that using the current and future population of the British Sailing Team's Junior and Youth sailors, that greater numbers will be added to this study design to be able to clarify whether the amount of sailors with significant growth post-17.5 years is systematic within the sport or a random result in this occasion. It is not clear from the data recorded of any indicators that distinguish these sailors, so it is proposed that to enhance the accuracy and understanding of the PAH prediction more research is needed to a) use a more suitable age for the classification of PAH i.e. 21 years and/or multiple measurements at least three months apart with no increase in height, and b) to try and understand the distinguishing factors of individuals that grow abnormally.

From the comparisons in agreement and accuracy of the two PAH prediction methods in this study accompanied with the accuracy reported in previous research, it was decided that the Khamis and Roche (1995) method was preferred to Sherar *et al.* (2005) for use in the prediction of PAH.

PAH Prediction and ideal height ranges at super-elite level in Olympic sailing

There is a limited amount of measured height data available in elite Olympic sailing, currently only the Finn and RS:X classes have published their data which is now between five and eight years old. This combined with the Self-reported data from the Olympic Data Feed in the last two Olympic Games is presented in elite data collected through measurement (International Finn Association, 2010; RS:X Class.com, 2012) and self-reported from the Olympic Data Feed in the Finn and RS:X classes are displayed in Table

6.1 and Table 6.2. With no control over the reporting of the Olympic Data Feed, this data would be ranked as least robust, similar to the estimates of top elite-level coaches (Figure 6.6), with the measured heights as the most robust evidence currently available for the understanding of height requirements in Olympic sailing.

It would appear that there was a slight increase in height within the Finn class since 2009 to 2016, though the ideal value proposed by the BST coaches remains within the original measured variation from 2009. Without a value to describe range or spread of the RS:X recorded data, it is difficult to compare all three methods. However it appears that there is variation in the mean values between the Top 10 and Top 15 in the World from 2011 to 2016, with the medal race sailors in the female RS:X fleet being shorter. In the men's RS:X fleet the mean heights of the Top 10 to Top 15 remain above 183 cm, with the British Sailing Team coaches suggesting a greater height of 183 to 192 cm as being ideal.

It was clear from the interviews with elite sailors and coaches from Chapter Three that height (and leverage) are key characteristics in successful transition up to and at the super-elite level of Olympic sailing, signified with the key quote of:

"As soon as you get to Olympic racing it [size] is non-negotiable – if you are not tall and fit you won't win races…. You have sailors that are really short that do well at about 50% of regattas, and then really averagely in the other half, so you need to be good in all conditions and exceptional in a couple."

With greater height comes a more effective lever arm to produce righting moment, that has a close relationship with boat speed (Cunningham and Hale, 2007; Larsson *et al.,* 1996), especially when the wind is increased (Mackie *et al.,* 1999), though even at the lower wind ranges a greater height may have more advantage if they are the same weight as explained within another quote:

"*you have someone who is 6ft 2 and someone who's 5ft 8 racing against each other, no matter how fit the short of person is they're always going to be giving away leverage - which turns into boat speed."*

These quotes combined with the review of Olympic sailing's physical requirements (Bojsen-Möller *et al.*, 2014) suggest that there is a level of 'morphological optimisation' that may be applied to elite sailing, as it appears that there are particular height bandwidths for performance across a range of conditions to be successful, which is supported through the elite British Sailing Team coach estimates.

The proposed use of PAH prediction must be used with caution, as although it has been shown that particular ideal ranges of height exist within elite sailing, there are many factors that combine to produce a successful elite athlete (MacNamara and Collins, 2011; Suppiah *et al.,* 2015; Vaeyens *et al.,* 2008). It is key to understand that the ranges of PAH prediction are based on mean data, and when considering the individual make-up of what is successful at the super-elite level in any sport, the potential need to accommodate for outliers must be acknowledged, as deficiencies in one area may be compensated for in another (Williams and Ericsson, 2005). PAH prediction should not be considered a predictor of success, though it will support an athlete's potential trajectory. It is worthwhile to remember that athletes' individual trajectories are non-linear through maturity and development, and performance is also impacted on by other areas such as skill acquisition and psychology (Malina, 2004).

This study has a number of strengths and limitations. The strengths include; all measurements being completed by ISAK accredited physiologists which ensures a level of accuracy in measurement, having the access to the top two elite coaches in the British Sailing Team, with one at least in each class having attended an Olympic Games including the most recent Games in Rio, observing height data broken down between genders and age groups allowed for a more detailed report and the use of cheaper/non-invasive methods of PAH prediction increase the benefit to other sports/populations. Limitations include; sample size of gender and age group splits, lack of reliable measured height data in elite and super-elite sailing, the low number and potential bias of British Sailing Team coaches in estimation of ideal heights, and the inability of methods to predict further growth after 17.5 years of age, particularly for males.

6.5 Practical applications

Considering the limitations of using coach estimates in terms of low sample size and potential bias, using the current estimations of ideal ranges for PAH in all the Olympic classes it would be possible to project a Youth sailor's PAH prediction to identify the likely Olympic class they may be best suited to anthropometrically within the error range identified in this study. Presented in this section is an example of how the PAH prediction could work with the current estimates of ideal height ranges for success at super-elite level in the Olympic classes (Figure 6.7). The examples below include PAH predictions for sailors in the 15.5 to 16.5 years age group:

a) A female sailor who is predicted to be 180 cm (50% CI [179.4 – 180.6 cm], 95% CI [178.4 – 181.6 cm]). Based on the 50% CI this sailor fits within the ideal range of most classes (FX helm, Nacra crew, 470 crew, Radial), on the shorter borderline for FX crew, but too tall for 470 helm and most likely too tall for RS:X. At 95% CI the 470 helm position remains outside the ideal limits, and more classes are at an increased possibly of becoming unlikely as being too short (470 crew, Radial and FX crew).

b) Male sailor who is predicted to be 177 cm with 50% CI [174.5 – 179.5 cm], 95% CI [169.7 – 184.3 cm]. At 50% CI the sailor would appear within ideal boundaries for the 470 helm, Nacra helm and on the borderline for 49er helm, although too short for the 49er crew, 470 crew, Laser, RS:X or Finn. When using the 95% CI this sailor may potentially fit into all classes apart from the Finn, but also could be outside of the ideal range by being too short for every class.

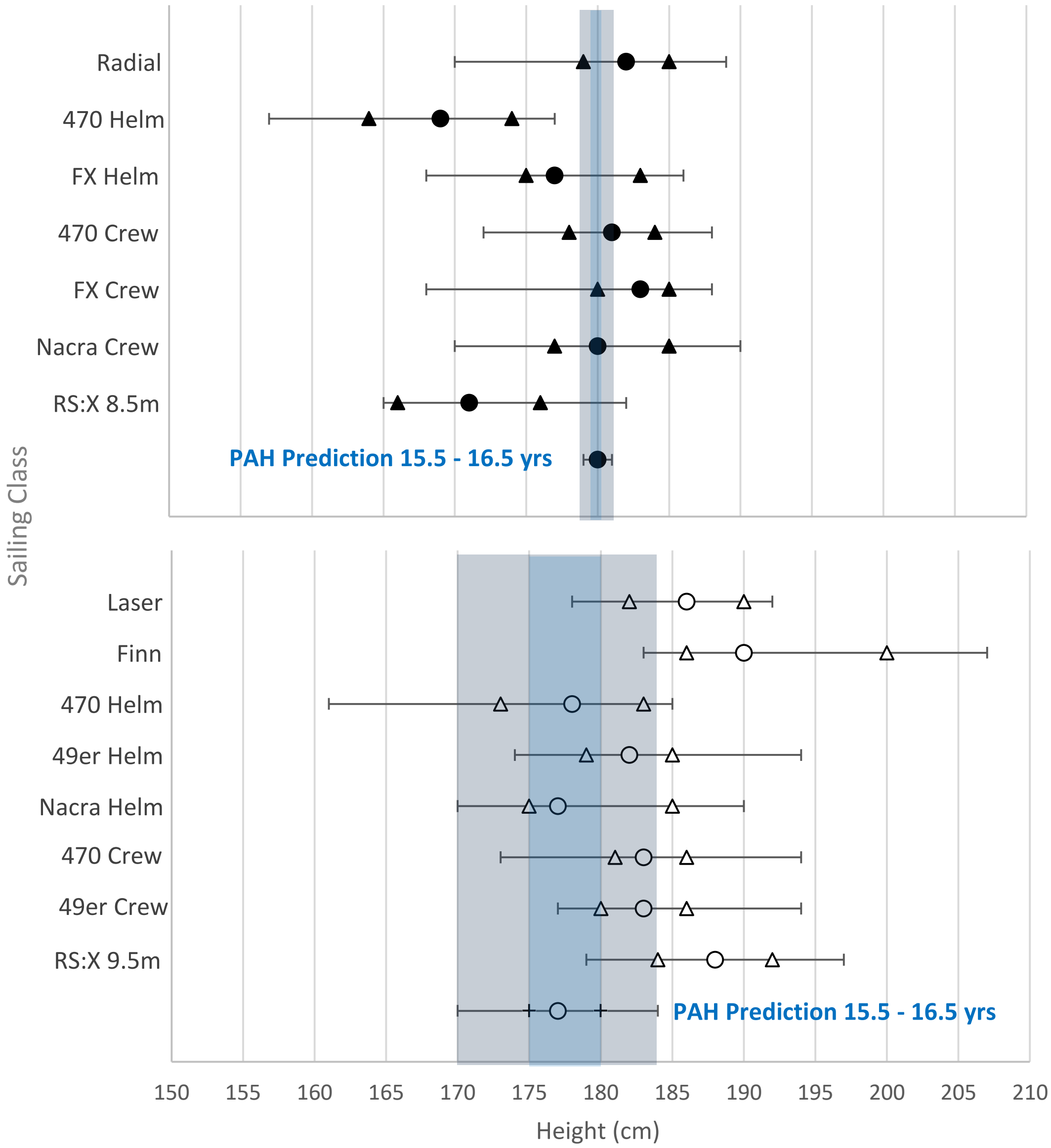

Figure 6.7 PAH prediction for sailors in the 15.5 – 16.5 years age group using Khamis and Roche (1995) method relative to estimated ideal height ranges of successful super-elite sailors in Olympic classes. Note: • – female, o – male, dark blue shaded area denotes 50% CI, light blue shaded area denotes 95% CI.

The Khamis and Roche (1995) method of PAH prediction has been chosen to be used within British Sailing Team's Olympic pathway physical testing battery due to exhibiting similar or improved agreement and accuracy when compared to actual PAH. Using the prediction information from this method using simple, cheap and non-invasive technique a sailor, coach, or manager may be able to identify likely and less likely developmental trajectories. When looking at the mass data of the Junior and Youth programme – it may be possible to identify if there are any particular gaps in the current crop of athletes to fit the ideal height ranges for super-elite success in the Olympic classes, possibly highlighting the need to engage in processes such as Talent transfer (Vaeyens *et al.,* 2008). It is clear from the CIs reported in this study that the PAH prediction would be a more accurate tool for females with the Olympic pathway potentially due to the increased potential for males to grow post-17.5 years.

The other application of employing the prediction of Khamis and Roche (1995) linked to physical profiling is to assess the maturation status of sailors within the Olympic pathway, by taking the current height and expressing that as a percentage of predicted PAH. So that within two sailors of the same height, the one with a greater percentage of predicted PAH would have less to grow and therefore be more mature. This method has previously been shown to have accordance with maturation status estimates using SA in youth football players (Malina *et al.,* 2007). This approach is evaluated as part of the next chapter and more detail on the assessment of maturation status via the percentage of PAH (%PAH) is discussed in section 7.2.2.

Chapter 7 Analysis of the Anthropometric, Maturational, and Physical characteristics of Junior and Youth classes within the Olympic pathway

7.1 Introduction

Elite level sailing research below adult Olympic level comprises of just a handful of papers, with no research involving double-handed boats or boardsailors. The focus instead being placed on the single-handed hiking positions in the Laser, Laser Radial, Byte and Optimist classes (Burnett *et al.,* 2012; Callewaert *et al.,* 2013a, 2013b, 2014a, 2014b; Tan *et al.,* 2006). Specifically, the number of single-handed hiking positions in Olympic sailing only constituted three out of 15 positions in the Rio 2016 Olympics and five out of 19 RYA elite pathway positions, therefore the lack of double-handed hiking, trapeeze and boardsailing research in pathway sailing is a significant gap in knowledge. This pattern is similar at Olympic level where the predominance of research investigate hiking, with fewer studies covering boardsailing and even less in the trapeeze positions.

The importance of understanding the physical requirements of sailing has increased due to the overall level of physicality increasing in more recent times, due to a combination of factors such as: increased level of competition, race format/rules, change of classes sailed and more advanced boat design (Bojsen-Möller *et al.*, 2014). It is the aim of sailors to navigate their way around a course with maximum boat speed, which is predominantly achieved by harnessing as much force in the sails as possible while keeping the boat flat by using the righting moment of the sailor (Evan, 2009). This righting moment is created from a function of height and body mass of the sailor (s), which is increased through physical exertion using the movements of hiking and trapeezing (described earlier in this thesis), or through providing propulsion via pumping, predominantly in the boardsailing RS:X class (Evan, 2009).

Previous research in Olympic sailing broadly categorised class types into hike, trapeeze and boardsailing (Bojsen-Möller *et al.*, 2007), this may have been too simplistic due to the complexities of different classes/positions within those brackets. Emerging within the hiking group are ‘hikers’ and ‘side hikers’ (Bojsen-Möller *et al.*, 2014), although the ‘hikers’ group can be further divided to ‘static’ and ‘dynamic’ hikers (Callewaert *et al.,* 2014b), based on boat design, movements involved in sailing, plus the ratio of sailor mass versus the mass of the boat. For the purposes of providing greater detail in the current and following chapter where possible, class types will be broken down into single-handed hiking (Hike1), double-handed hiking (Hike2), trapeeze (Trap) and boardsailing (Board). For details of the division of class type plus the dimensions of all RYA Olympic and pathway classes see Table 7.1.

Table 7.1 Class types and dimensions within Olympic and RYA pathway classes.

Class	Helm	Crew	Level	Total Sail Area (m^2)	Hull Weight (kg)	Length (m)
Optimist	Hike1	-	Junior	3.6	35	2.30
Topper	Hike1	-	Junior	4.2	43	3.40
Laser 4.7	Hike1	-	Junior	4.7	60	4.23
Cadet	Hike2	Hike2	Junior	9.5	54	3.22
Mirror	Hike2	Hike2	Junior	11.7	61	3.30
RS Feva	Hike2	Hike2	Junior	14.4	63	3.63
Techno 293	Board	-	Junior	6.8	12	2.93
Laser Radial	Hike1	-	Youth/Olympic	5.7	60	4.23
Laser	Hike1	-	Youth/Olympic	7.1	60	4.23
420	Hike2	Trap	Youth	19.2	80	4.20
29er	Hike2	Trap	Youth	27.5	70	4.45
Spitfire	Trap	Trap	Youth	38.0	139	5.00
RS:X 8.5m	Board	-	Youth/Olympic	8.5	16	2.86
Finn	Hike1	-	Olympic	10.0	107	4.50
470 (M & F)	Hike2	Trap	Olympic	28.3	120	4.70
49er	Trap	Trap	Olympic	59.2	125	5.00
49er FX	Trap	Trap	Olympic	44.7	125	5.00
Nacra-17	Trap	Trap	Olympic	39.1	138	5.25
RS:X 9.5m	Board	-	Olympic	9.5	16	2.86

Note: M & F – Male and Female

Bojsen-Möller and colleagues have been the leading group to investigate physical and anthropometrical characteristics across multiple Olympic classes, concluding in their most recent review (2014) that distinct differences occur in both areas between class types and the relative importance of these characteristics also vary based on the role of the sailor and the vessel they race. This is primarily attributed to the demand that the boat places on its crew, specifically the sailor to vessel weight ratio and total sail area (Table 7.1). In the case of weight ratio this is simplified in Hike1 and Board classes as there is only one sailor, therefore the greater the sailor to vessel weight ratio the more impact physical movements (dynamic hiking and pumping) will have on speed (Bojsen-Möller *et al.*, 2007; Vogiatzis and De Vito, 2014). When considering total sail area, similar to weight ratio, it is more straightforward in the Hike1 classes, for example the Finn class possesses a greater sail area to the Laser (10.0 vs. 7.1 m^2) which creates greater forces at the toe strap and mainsheet when sailed in the same wind strength, requiring a greater opposing force (righting moment) and physical capability to keep the boat flat (Mackie *et al.,* 1999). In the only Olympic Hike2 position (470 Helm) the total sail area is much greater than any Hike1 class (28.3 m^2) however the trapeezing crew creates a much greater righting moment by standing on the side of the boat versus leaning over, so the physical and anthropometrical requirement of the helm is much lower (see Figure 1.3). This was reflected in Bojsen-Möller *et al.* (2007) where double-handed helmsmen were found to be shorter and lighter than the dynamic hikers (height 178 ± 6 vs. 186 ± 2 cm, and body mass 63.7 ± 5.9 vs. 68.7 ± 2.2 kg respectively) less variation was generally observed between class types in female sailors. Evidence of the increase in Laser sailors' anthropometry specifically was noted as more recent data within the same study in 2002 (height 1.81 ± 0.05 m and body mass 80.3 ± 2.7 kg), as a comparison between Hike1 classes Finn sailors were measured at 1.84 ± 0.04 m and weighed 93.5 ± 10.8 kg reflecting the greater righting moment requirement. Differences in heights of Olympic class sailors was estimated by elite BST coaches in the previous chapter, highlighting the range in current (2016) racing (see Figure 6.6).

The physical demands of sailing are not entirely understood due to a lack of objective measurements on water (Bojsen-Möller *et al.*, 2014), made difficult by the ever changing environment of wind, sea state and temperature plus the barriers of getting expensive equipment in contact with salt water. In the absence of this data, scrutinising an elite sample with controlled measurements linked to on-water/simulated performance will lead to a greater understanding. Through this methodology it has been concluded that Olympic sailing produces significant physical requirements (Bojsen-Möller *et al.*, 2014). Hiking sailors displayed high levels of strength and endurance in knee extensors (Aagaard *et al.,* 1998; Bojsen-Möller *et al.*, 2007; Vangelakoudi *et al.,* 2007), trunk (Aagaard *et al.,* 1998) and upper body pulling muscles (Mackie and Legg, 1999; Plyley *et al.,* 1985) alongside a moderate to high level of aerobic capacity of approximately 55 to 61 $mL \cdot kg^{-1} \cdot min^{-1}$ (see section 2.5.1.4). Within the small amount of research into trapeeze sailors, maximal knee extension strength and upper body strength was found to be similar or higher than hiking sailors (Maisetti *et al.,* 2006; Plyley *et al.,* 1985), with aerobic capacity following a similar pattern (57 to 64 $mL \cdot kg^{-1} \cdot min^{-1}$; Bojsen-Möller *et al.*, 2007). A high level of agility and specifically anaerobic capacity in 49er crews is also required (Allen and DeJong, 2006) potentially exacerbated by proposed race format changes. Board sailors have been found to possess the highest aerobic capacity (greater than 65 $mL \cdot kg^{-1} \cdot min^{-1}$; Castagna *et al.,* 2008) combined with high levels of muscular force required during pumping, especially when sailing downwind (Buchanan *et al.,* 1996). This has led authors to compare the demands of this class type to that of endurance events such as cycling or rowing (Bojsen-Möller *et al.*, 2014). For a detailed review on physical requirements in Olympic sailing please see Section 2.5.

As mentioned earlier in this chapter, less is known about elite Junior and Youth sailing, with all research studies examining Hike1 class types, predominantly using specific testing designs focusing in on the hiking movements/muscles using dynamometers or custom-built simulated hiking. These studies made comparisons between elite and non-elite Hike1 sailors, revealing knee extensor and trunk strength were important for simulated hiking (HM_{180} and Bucket test) and that HM_{180}/Bucket test performance and body mass were key factors to distinguish performance level in hiking conditions (mean wind strength >10-12kn) (Burnett *et al.,* 2012; Callewaert *et al.,* 2014b*;* Tan *et al.,* 2006). However when compared to an untrained age-matched group, Optimist sailors revealed similar knee extensor strength (151 ± 43.9 vs. 153.3 ± 55.3 Nm), but were found to be more fatigue resistant in a simulated hiking task (Callewaert *et al.,* 2013b). Suggesting that elite Junior sailors were not extraordinary when it came to strength, but were able to outperform untrained controls using more efficient technique and/or possible morphological adaptation from a greater time spent sailing.

In the context of TDE it is argued that tests without a high sport-specific skill should be employed when examining physical development in youth athletes, so that scores are not biased to the amount of sport-specific training or the length of time in the sport's pathway (Lidor *et al.,* 2009). Younger athletes should be profiled against a range of movements/abilities as these relate to developing robustness to cope with the increasing demands of the sport (Lloyd *et al.,* 2015b). These tests should not be seen as predictors of success, but key information as to how to best support the individual development of the athlete to allow for them to achieve their potential (Lawton *et al.,* 2012). In sailing this is particularly relevant as sailors have a number of possible trajectories available to them as they progress up the Olympic pathway (Figure 1.10) across a range of class types. Potentially more important to the argument for inclusion of non-specific tests in the Olympic pathway lie in the uncertainty of the Olympic classes that will exist when pathway sailors reach adulthood, as can be seen in Figure 1.6, the Olympic classes may change every four-year cycle, possibly rendering previous specific test data meaningless.

Non-specific physical characteristics have been shown to distinguish elite and non-elite sailors within and between performance level in Junior and Youth classes (Callewaert *et al.,* 2014b). Elite Optimist sailors outscored their non-elite counterparts in tests from the EUROFIT battery (Council of Europe, 1988) in motor co-ordination, while Youth dynamic hiking sailors displayed greater anaerobic and aerobic capacity. Aerobic capacity of Youth dynamic hiking sailors were comparable to elite football players (59.2 ± 3.2 $mL \cdot kg^{-1} \cdot min^{-1}$; Le Gall *et al.*, 2010) and greater than elite volleyball players (43 ± 6.1 $mL \cdot kg^{-1} \cdot min^{-1}$; Gabbett *et al.,* 2007).

What is unknown within elite Junior and Youth sailing is the impact of maturation on anthropometrical and physical fitness characteristics. In other sports, athletes who are more advanced in maturation exhibit greater height, mass and physical performance, lending themselves to selection into positions in which these characteristics hold an advantage (Malina *et al.,* 2004; Meylan *et al.,* 2010; Mohamed *et al.,* 2009). Selection based on these factors contains risk, as research has shown that early maturing athletes do not maintain these advantages into adulthood (Pearson *et al.,* 2006; Vaeyens *et al.,* 2008). Late maturers, who have been able to continue within talent programmes that favour anthropometry and physical fitness are suggested to have had to develop physical and non-physical abilities to compete (Gray and Plucker, 2010; MacNamara and Collins, 2011; Suppiah *et al.,* 2015) which is assumed to result in a more multilaterally skilled athlete (Vandendriessche *et al.,* 2012).

The aim of this study is to compare and contrast the anthropometric, maturation and physical fitness characteristics of female and male Junior and Youth classes within the Olympic pathway. This will be completed by using the British Sailing Team's physical testing battery further rationalised from sailor/coach interviews (Chapter 4) and confirmed in Chapters five and six. It is anticipated that pathway classes that create greater physical demands, from a combination of sailor to boat mass ratio or an increased sail area, will exhibit greater anthropometry and physical characteristics similar to what is observed in Olympic class sailing (Bojsen-Möller *et al.*, 2014).

7.2 Methods

The population described in this study constitute the initial five year period of a longer-term longitudinal data collection project within British Sailing to track the physical characteristics of Olympic sailors. This study was approved via the ethics committee of the University of Chichester. Informed consent was received from parents and sailors as part of acceptance of a place within the Olympic pathway and/or attendance at physical profiling sessions.

7.2.1 Participants

The population comprised of elite Junior and Youth sailors in the United Kingdom, with representation from England, Scotland and Wales. Selection into elite squads is primarily based on performance results from an RYA-appointed selection series comprising of a number of regattas, ideally three or more, with high quality racing in a range of environments i.e. inland, open sea, although this is not always achieved due to the weather and conditions. Sailors are selected onto a number of Junior and Youth sailing classes as follows: Junior – Optimist, Topper, Laser 4.7, RS Feva, Cadet, Mirror and Techno, Youth – 420, 29er, Spitfire, Laser, Laser Radial and RS:X (for more information on these classes please see section 1.6). Sailors selected onto 'Transitional' squads between Junior and Youth level were omitted from this study as were felt to be too low-ranked to represent elite status.

At the end of the first round of pathway profiling (December 2012) 149 sailors were tested. Each year a maximum of two pathway profiling sessions were conducted per sailor (Winter: September to December, and Spring: February to April) by the end of the five year profiling period (December 2016) 495 sailors had been tested between one to nine times, yielding a total of 1,395 data points. For general characteristics of the population within this study please see Table 7.2.

Table 7.2 Olympic pathway characteristics between December 2012 to 2016

	n	Data points	Age (years)	Range
Dec 2012	149	149	14.9 ± 1.82	(11.0 - 20.4)
Female	58	58	14.9 ± 1.82	(11.0 - 18.4)
Male	91	91	15.0 ± 1.83	(11.1 - 20.4)
Junior	88	88	13.6 ± 0.99	(11.0 - 15.6)
Youth	61	61	16.8 ± 0.98	(14.2 - 20.4)
Dec 2016	495	1395	15.2 ± 1.83	(11.0 - 20.7)
Female	192	530	15.2 ± 1.82	(11.0 - 20.1)
Male	303	865	15.1 ± 1.84	(11.0 - 20.7)
Junior	372	797	13.8 ± 1.00	(11.0 - 16.3)
Youth	123	598	17.0 ± 0.94	(13.9 - 20.7)

7.2.2 Procedures

For detailed explanations of procedures completed within the study please see Chapter 4 (anthropometry, T-test, SLJ, 20 m SRT), section 5.2.2 (Press-ups and Supine pulls) and section 6.2.2 (predicted PAH). Pre-reading for sailors outlining the procedures and information on pre-testing preparation can be found in Appendix 7.

Maturation Assessment

As directed by the findings of Chapter 6, estimation of maturation status and maturity timing were based on the work of Khamis and Roche (1995). Mid-parental height was recorded via self-reporting online via selection registration to the nearest half-inch. To allow for overestimation of self-reported height the Epstein adjustment equation was applied (Epstein *et al.,* 1995).

Maturation status was expressed as percentage of predicted PAH (%PAH). Estimated maturity timing was estimated using the *z*-score of the sailor's %PAH compared to female and male normative data from the Berkley Guidance study (Bayer and Bayley, 1959). Criteria for maturity timings was as follows: <-1.0 late, -1.0 to -0.5 slightly late, -0.5 to 0.5 on time, 0.5 – 1.0 slightly early, >1.0 early. Estimates of PHV classification were based on %PAH from UK 1990 age and gender-specific reference standards (Freeman *et al.,* 1990) and were as follows: <89%PAH pre-PHV, 89 to 95%PAH circa-PHV, >95%PAH post-PHV. Which corresponds to the range of circa-PHV of 11.25 to 13 years in females and 13.5 to 15 years in males (for 1990 Reference tables see Appendix 5).

7.2.3 Data Analysis

Analysis of the initial five year data collection were grouped into female and male groups initially, then split into the respective Junior and Youth classes. The analyses were divided into anthropometry, maturation and physical using descriptive statistics. These were chosen as each sailor had the potential for up to five data points within the same class resulting in a lack of independence. Consideration was given to averaging multiple data points however it was felt that this detracted from the aim of the study and confused the meaning of the data. Another option was to look at multiple cross-sectional analyses for each profiling session over the course of the five years, however when classes were split into gender groups there was a lack of sample size, in some cases as low as two sailors. All anthropometrical and maturation data are presented as raw data, physical test scores are presented both in raw and percentile methods. Percentiles were calculated from the range of scores performed in tests over the five year period, with the best female/male score in each test representing 100%, and the worst 0%. Statistics all displayed as means ± S.D., differences reported were based on identifying interactions between classes/positions where means plus S.D. do not overlap a difference was observed.

7.3 Results

This section will describe the results of anthropometry, maturation and physical fitness in order, with Junior classes presented first followed by the Youth classes.

7.3.1 Anthropometry

Similar differences were observed between the heights of female and male Junior pathway classes; Laser 4.7 class were the tallest (168.6 ± 4.4 and 170.3 ± 6.3 cm respectively) with differences observed to the Optimist and Cadet Crew position, and Mirror class in female only (Table 7.3 and Table 7.4). Laser 4.7 class were the heaviest (61.3 ± 4.5 and 58.5 ± 5.0 kg respectively), with differences observed versus Optimist and Cadet Crew in females and males approaching similar difference between Optimist and Topper. Differences were also observed between Laser 4.7 and Mirror and RS Feva classes in females only (Table 7.3 and Table 7.4). The interaction between height and mass displayed in Figure 7.1 continues the theme of greater anthropometric size in Laser 4.7 class, adding more detail in displaying greater variation within male versus female Junior classes.

At Youth level no clear height differences were observed in female classes (Table 7.5), in males however the Laser class was taller than the Hike2 classes (186.1 ± 5.2 versus 174 ± 4.8 and 174 ± 5.0 cm in 420 and 29er Helms respectively) (Table 7.6). In females the Laser Radial was heaviest, greater than Hike2 classes (68.6 ± 5.6 versus 54.6 ± 4.8 and 56.1 ± 4.5 kg in 420 and 29er Helms respectively). The Laser class was heaviest (78.4 ± 5.8 kg) different to Hike2 and Trap classes, with smaller differences between Multi-hull and RS:X 8.5m. When considering the height x mass interaction, the Laser Radial remained the largest female class, with differences with Hike2 classes. In males, the Laser class was largest with Laser Radial approaching differences versus both Hike2 classes (Figure 7.1).

Table 7.3 Anthropometrical, maturation and physical fitness descriptive statistics for Female Junior pathway classes

	Techno n = 42	Optimist n = 44	Topper n = 71	Laser 4.7 n = 38	Cadet Helm n = 25	Cadet Crew n = 17	Mirror n = 30	RS Feva n = 31
Age (years)	14.5 ± 0.9	13.2 ± 0.9	14.2 ± 0.8	14.3 ± 0.9	13.9 ± 0.7	12.1 ± 0.9	13.2 ± 1.0	13.9 ± 0.6
Anthropometry								
Height (cm)	167.5 ± 6.1	156.3 ± 6.9	163.3 ± 6.6	168.6 ± 4.4	166.0 ± 4.7	152.9 ± 8.2	156.8 ± 7.1	162.6 ± 5.0
Body mass (kg)	54.2 ± 6.0	44.4 ± 5.6	56.2 ± 6.1	61.3 ± 4.5	53.6 ± 6.0	43.4 ± 10.2	44.6 ± 6.2	50.5 ± 4.6
Maturation								
%PAH (%)	98.3 ± 1.1	94.5 ± 3.1	97.9 ± 1.8	98.6 ± 0.7	97.4 ± 1.5	90.9 ± 4.7	94.4 ± 3.2	97.0 ± 1.2
Z Score	-0.5 ± 0.8	-0.9 ± 0.7	-0.3 ± 0.7	0.1 ± 0.8	-0.5 ± 0.9	-0.6 ± 0.7	-0.9 ± 0.5	-0.6 ± 0.7
PAH (cm)	170.3 ± 5.1	165.3 ± 4.3	166.8 ± 5.6	170.9 ± 4.0	170.4 ± 3.4	168.3 ± 5.9	166.1 ± 4.9	167.7 ± 4.1
Physical								
T-test (sec)	12.25 ± 0.62	12.12 ± 0.88	12.42 ± 1.20	12.16 ± 0.73	11.97 ± 0.72	12.79 ± 0.91	12.52 ± 0.80	12.53 ± 0.57
SLJ (m)	1.75 ± 0.16	1.75 ± 0.16	1.65 ± 0.23	1.76 ± 0.20	1.71 ± 0.15	1.58 ± 0.18	1.70 ± 0.17	1.64 ± 0.13
Press-ups (reps)	8.6 ± 6.4	6.7 ± 5.4	6.4 ± 5.9	5.4 ± 5.2	3.5 ± 3.0	4.8 ± 3.4	1.7 ± 1.7	4.5 ± 3.8
Supine Pulls (reps)	16.2 ± 7.8	12.0 ± 5.6	11.6 ± 6.7	15.2 ± 8.0	6.3 ± 4.7	6.7 ± 4.6	9.7 ± 3.5	8.0 ± 5.7
Bleep Distance (m)	1,290 ± 208	1,489 ± 275	1,251 ± 307	1,362 ± 242	1,374 ± 311	1,134 ± 279	1,394 ± 271	1,286 ± 166
Overall Score (%)	54 ± 17	54 ± 19	45 ± 24	51 ± 19	44 ± 16	33 ± 11	41 ± 7	40 ± 12

Table 7.4 Anthropometrical, maturation and physical fitness descriptive statistics for Male Junior pathway classes

	Techno n = 47	Optimist n = 115	Topper n = 154	Laser 4.7 n = 64	Cadet Helm n = 22	Cadet Crew n = 11	Mirror n = 14	RS Feva n = 72
Age (years)	14.3 ± 1.1	13.1 ± 1.0	14.1 ± 0.7	14.4 ± 0.6	14.1 ± 0.5	12.4 ± 1.1	13.7 ± 0.6	13.5 ± 0.9
Anthropometry								
Height (cm)	166.9 ± 8.4	155.0 ± 8.3	167.9 ± 8.3	170.3 ± 6.3	164.4 ± 9.2	150.2 ± 5.9	164.2 ± 7.3	160.2 ± 7.8
Body mass (kg)	55.3 ± 7.9	42.6 ± 6.5	55.1 ± 7.9	58.5 ± 5.0	53.4 ± 7.0	41.7 ± 6.9	54.6 ± 8.6	47.4 ± 7.2
Maturation								
%PAH (%)	92.2 ± 4.4	87.2 ± 4.1	92.4 ± 3.4	93.3 ± 2.7	92.0 ± 2.8	85.2 ± 4.0	90.8 ± 2.8	89.8 ± 3.8
Z Score	0.1 ± 0.6	-0.2 ± 0.7	0.4 ± 0.6	0.3 ± 0.4	0.3 ± 0.5	-0.2 ± 1.1	0.5 ± 0.6	0.2 ± 0.5
PAH (cm)	181.0 ± 3.0	177.9 ± 6.0	181.6 ± 5.6	182.6 ± 5.5	178.6 ± 6.7	176.4 ± 5.8	180.8 ± 5.2	178.4 ± 4.8
Physical								
T-test (sec)	11.73 ± 1.05	11.98 ± 0.86	11.5 ± 0.77	11.14 ± 0.78	12.29 ± 1.79	12.67 ± 0.85	12.42 ± 0.96	11.69 ± 0.80
SLJ (m)	1.90 ± 0.28	1.76 ± 0.20	1.92 ± 0.21	1.99 ± 0.22	1.64 ± 0.29	1.56 ± 0.21	1.82 ± 0.28	1.85 ± 0.18
Press-ups (reps)	19.1 ± 8.6	11.1 ± 7.9	14.0 ± 7.0	13.2 ± 6.5	11.8 ± 7.5	6.4 ± 5.1	7.3 ± 5.7	13.4 ± 7.0
Supine Pulls (reps)	21.3 ± 13.7	15.1 ± 7.7	15.2 ± 8.6	20.8 ± 8.2	13.5 ± 6.6	12.1 ± 7.9	14.8 ± 6.0	15.2 ± 8.8
Bleep Distance (m)	1,690 ± 329	1,615 ± 307	1,634 ± 330	1,774 ± 293	1,516 ± 377	1,186 ± 320	1,469 ± 284	1,644 ± 337
Overall Score (%)	49 ± 23	32 ± 16	40 ± 16	49 ± 18	30 ± 21	17 ± 12	27 ± 16	38 ± 19

Table 7.5 Anthropometrical, maturation and physical fitness descriptive statistics for Female Youth pathway classes

	Laser Radial n = 44	420 Helm n = 47	29er Helm n = 31	420 Crew n = 44	29er Crew n = 33	Multi-hull n = 12	RS:X 8.5m n = 21
Age (years)	16.9 ± 1.2	16.7 ± 0.8	17.2 ± 0.7	16.8 ± 0.9	17.0 ± 0.9	17.3 ± 0.9	17.0 ± 0.7
Anthropometry							
Height (cm)	170.6 ± 5.0	164.0 ± 4.8	166.0 ± 3.4	169.7 ± 3.6	170.2 ± 7.8	169.2 ± 4.7	167.7 ± 2.8
Body mass (kg)	68.6 ± 5.6	54.6 ± 4.8	56.1 ± 4.5	62.2 ± 5.2	64.4 ± 5.7	62.7 ± 2.1	62.0 ± 2.9
Maturation							
%PAH (%)	99.6 ± 0.3	99.3 ± 0.2	99.5 ± 0.2	99.5 ± 0.2	99.5 ± 0.3	99.6 ± 0.3	99.5 ± 0.2
Z Score	-0.8 ± 0.9	-1.5 ± 0.8	-1.3 ± 0.6	-0.9 ± 0.7	-1.3 ± 1.1	-0.8 ± 1.1	-1.3 ± 0.6
PAH (cm)	171.3 ± 4.8	165.1 ± 4.9	166.8 ± 3.4	170.6 ± 3.4	171.0 ± 7.7	169.9 ± 4.2	168.6 ± 2.8
Physical							
T-test (sec)	11.96 ± 0.52	11.63 ± 0.69	11.77 ± 0.54	11.83 ± 0.65	11.76 ± 0.61	11.50 ± 1.24	12.51 ± 0.63
SLJ (m)	1.80 ± 0.16	1.83 ± 0.18	1.79 ± 0.14	1.80 ± 0.14	1.83 ± 0.19	1.81 ± 0.33	1.76 ± 0.20
Press-ups (reps)	9.2 ± 6.0	13.0 ± 5.6	9.5 ± 4.3	11.6 ± 5.8	10.6 ± 7.1	11.9 ± 9.9	9.6 ± 6.0
Supine Pulls (reps)	17.9 ± 5.1	21.8 ± 9.6	21.2 ± 6.3	16.4 ± 6.7	21.7 ± 6.6	19.3 ± 13.7	21.3 ± 9.9
Bleep Distance (m)	1,354 ± 213	1,566 ± 265	1,349 ± 213	1,404 ± 293	1,392 ± 227	1,576 ± 286	1,470 ± 247
Overall Score (%)	62 ± 15	73 ± 14	67 ± 10	66 ± 17	70 ± 16	76 ± 22	60 ± 21

Table 7.6 Anthropometrical, maturation and physical fitness descriptive statistics for Male Youth pathway classes

	Laser Radial n = 70	Laser n = 42	420 Helm n = 54	29er Helm n = 61	420 Crew n = 34	29er Crew n = 39	Multi-hull n = 23	RS:X 8.5m n = 43
Age (years)	17.0 ± 0.6	18.2 ± 0.8	16.6 ± 0.9	16.9 ± 0.7	16.5 ± 1.0	16.5 ± 0.8	17.0 ± 1.6	17.2 ± 0.6
Anthropometry								
Height (cm)	181.2 ± 5.4	186.1 ± 5.2	174.1 ± 4.8	174.1 ± 5.0	175.7 ± 5.1	177.4 ± 4.8	176.3 ± 6.8	179.5 ± 4.1
Body mass (kg)	70.9 ± 4.0	78.4 ± 5.8	59.7 ± 5.9	62.0 ± 6.5	62.6 ± 6.4	65.1 ± 4.8	67.7 ± 4.9	68.4 ± 6.5
Maturation								
%PAH (%)	99.3 ± 1.2	100.2 ± 0.2	98.7 ± 1.6	99.5 ± 1.0	98.6 ± 1.7	98.9 ± 1.4	98.8 ± 1.9	99.7 ± 0.8
Z Score	0.6 ± 0.4	1.0 ± 0.2	0.6 ± 0.6	0.7 ± 0.4	0.5 ± 0.4	0.6 ± 0.4	0.7 ± 0.4	0.7 ± 0.3
PAH (cm)	182.5 ± 5.0	185.7 ± 5.5	176.3 ± 5.3	175.1 ± 5.1	178.2 ± 6.1	179.4 ± 3.9	178.4 ± 5.2	180.1 ± 4.0
Physical								
T-test (sec)	10.50 ± 0.55	10.52 ± 0.49	10.55 ± 0.59	10.50 ± 0.44	10.63 ± 0.51	10.46 ± 0.60	10.45 ± 0.57	10.70 ± 0.45
SLJ (m)	2.29 ± 0.18	2.30 ± 0.22	2.20 ± 0.19	2.22 ± 0.19	2.20 ± 0.10	2.21 ± 0.21	2.31 ± 0.19	2.27 ± 0.18
Press-ups (reps)	26.8 ± 6.3	29.5 ± 6.3	20.4 ± 10.6	23.4 ± 9.2	25.6 ± 7.0	22.2 ± 10.2	22.2 ± 7.6	24.9 ± 6.8
Supine Pulls (reps)	29.1 ± 10.4	27.6 ± 8.3	24.3 ± 7.8	30.1 ± 11.1	27.8 ± 8.9	29.3 ± 10.0	32.7 ± 12.6	30.8 ± 7.2
Bleep Distance (m)	2,095 ± 224	2,011 ± 276	2,094 ± 224	1,971 ± 284	1,943 ± 234	2,015 ± 335	2,072 ± 223	2,103 ± 265
Overall Score (%)	80 ± 11	79 ± 9	70 ± 16	75 ± 14	74 ± 12	72 ± 18	77 ± 12	77 ± 12

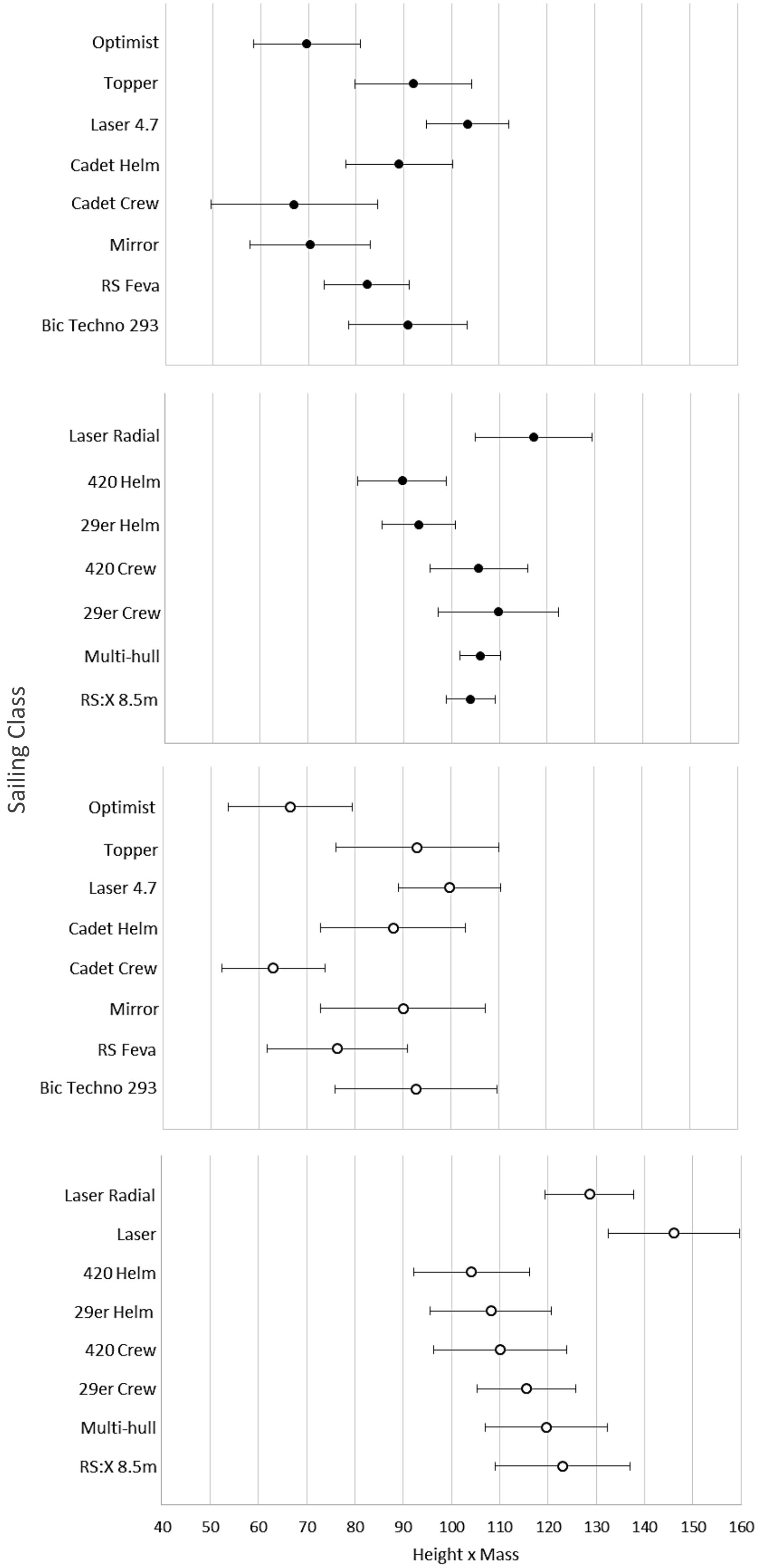

Figure 7.1 Mean Height x Mass of pathway classes. Note: • – female, o – male, error bars represent one S.D.

7.3.2 Maturation

In Junior females Optimist, Mirror and Cadet Crew were the least mature classes reported from a lower percentage of predicted PAH, Cadet Crew was the most immature (90.9 ± 4.7%) (Table 7.3). The above were the only classes who possessed >10% of sailors who were either pre- or circa-PHV (>45%) (Figure 7.3). Mean ages in these classes were below 13.2 years compared to the other classes > 13.9 years. Female Junior classes were found to be generally on-time or later in maturity status (z-score of maturity timing = 0.1 to -0.9), no greater than 25% of classes were estimated to be slightly early or early maturers (Figure 7.2). Predictions of PAH were similar between all classes. In male Junior classes a similar pattern emerged with the lower age and maturation status in Optimist and Cadet Crew aged <12.9 years compared to >13.6 years in other classes (Table 7.4) and possessing >60% of sailors who were pre-PHV versus <35% in other classes (Figure 7.3). The majority of male Junior classes were on-time or earlier in maturity timing (>70%) apart from Mirror class (40%) (Figure 7.2).

Female Youth classes appeared to be more homogenous in maturation status as all were estimated to be post-PHV (Figure 7.3), mean age of classes ranged from 16.7 to 17.2 years (Table 7.5). All classes were estimated to be slightly late or later in maturity timing with Z scores averaged -0.8 to -1.5 with no more than 8% estimated as slightly early or earlier (Figure 7.2). Predicted PAH in Laser Radial and Trap were found to be higher than Hike2 classes (>170.6 vs <166.8 cm). Male Youth classes were found to be advanced in maturation status as almost all were estimated to be post-PHV apart from 29er Helm and Multi-hull who had <10% of sailors circa-PHV (Figure 7.3). In contrast to females, the majority of classes were estimated to be slightly early to earlier maturers, averaging 0.5 to 1.0 in maturity z-score (Table 7.6) with only 420 Helm class possessing <5% late maturers (Figure 7.2). Predicted PAH was greatest in Laser and Laser Radial (Hike1) classes followed by RS:X 8.5m then Trap and Hike2 classes (Table 7.6).

7.3.3 Physical Fitness

No differences were observed between specific classes in any physical fitness variables within gender and level groups (female Junior, male Junior, female Youth or male Youth). Cadet Crew in both female and male Junior classes were found to be the least physically fit, with Bic Techno 293 and Laser 4.7 (in male only) exhibiting a trend for higher strength scores (Table 7.3 and Table 7.4).

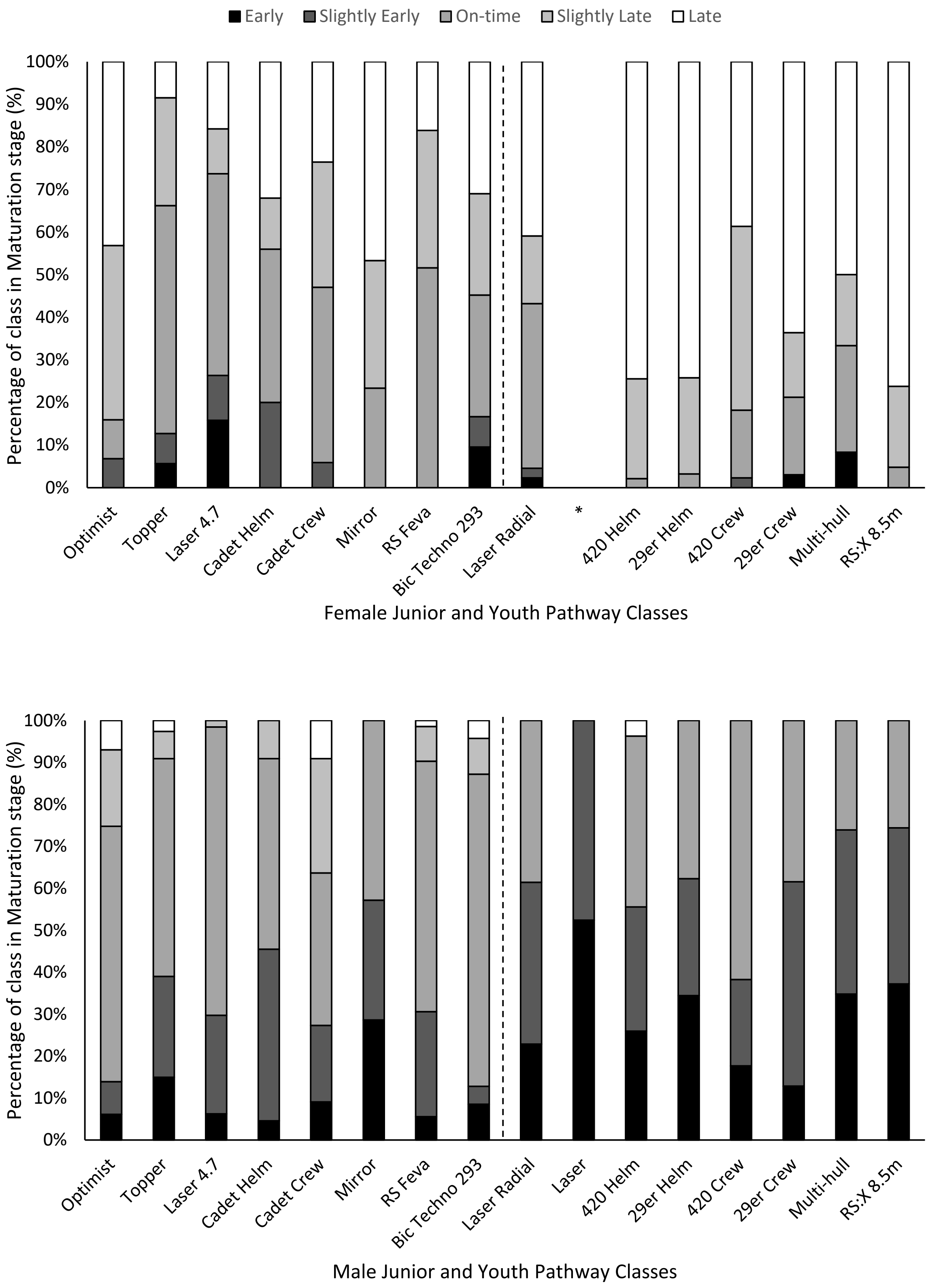

Figure 7.2 Maturity timing of pathway classes. Vertical dotted line represents division between Junior and Youth level. Note: * bar is left blank to allow vertical comparison, as females do not sail the Laser

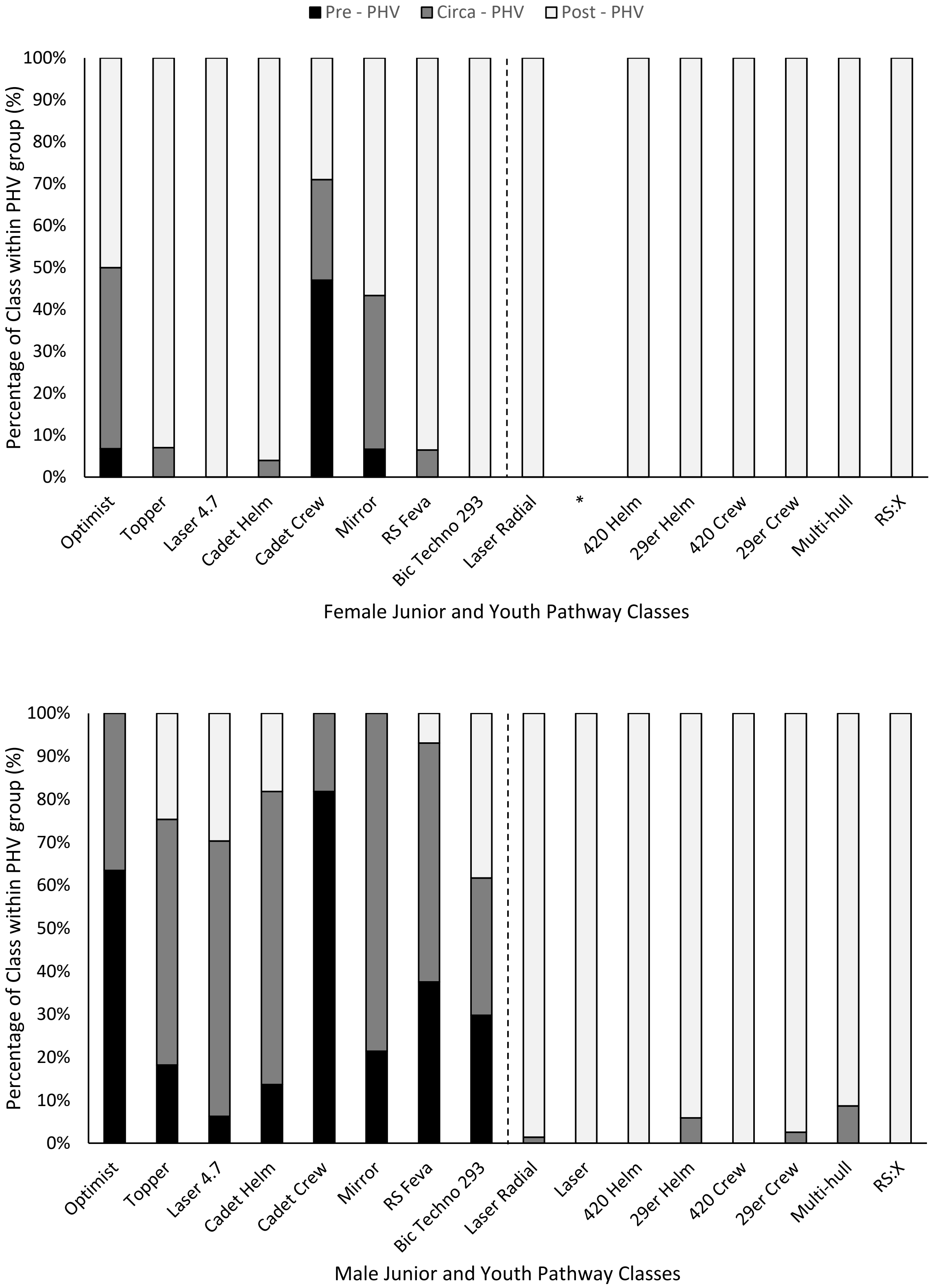

Figure 7.3 Maturation status of pathway classes relative to estimated PHV. Vertical dotted line represents division between Junior and Youth level. Note: * bar is left blank to allow vertical comparison, as females do not sail the Laser

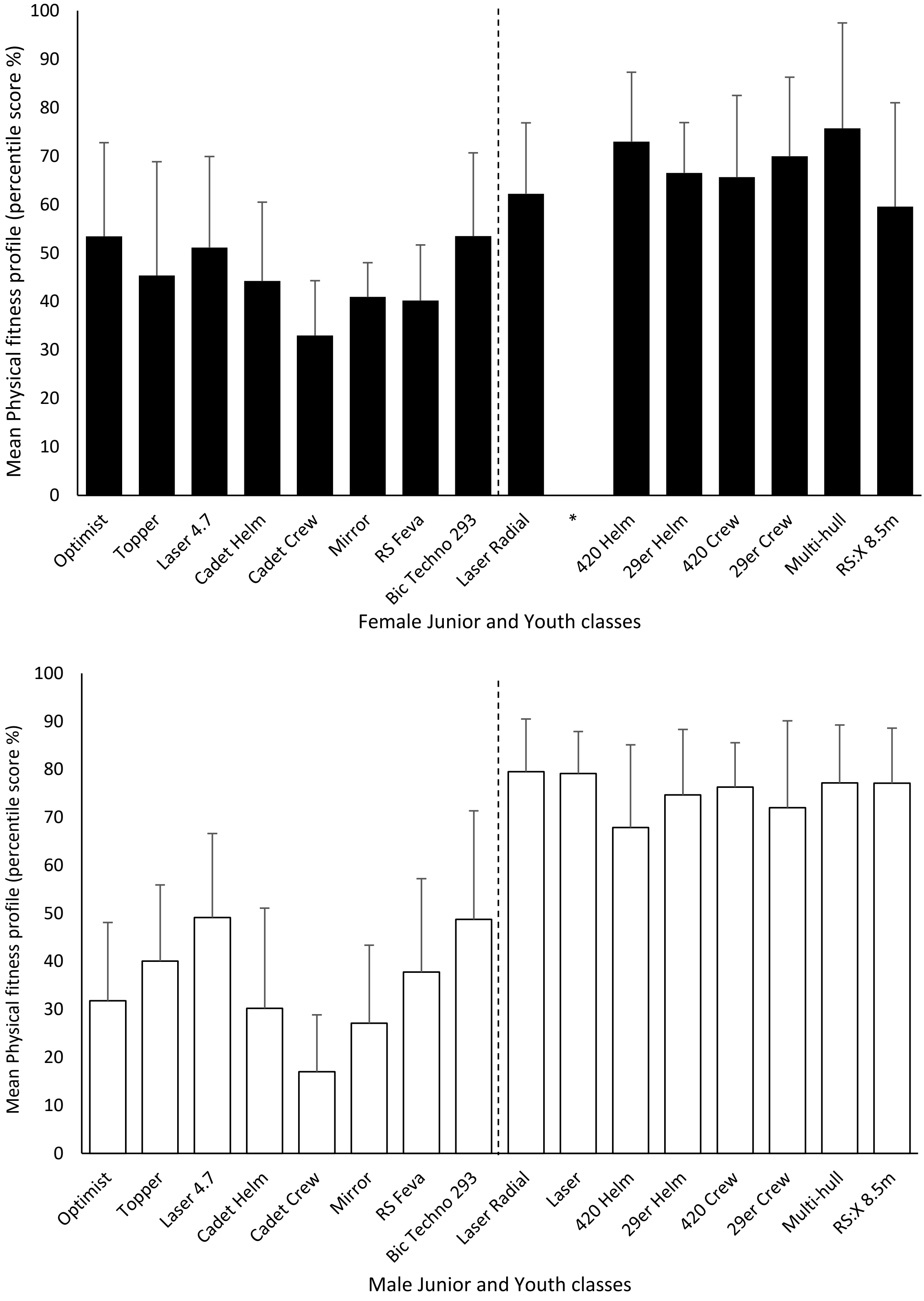

Figure 7.4 Mean Physical fitness scores of pathway classes (percentile score). Vertical dotted line represents division between Junior and Youth level. Note: * bar is left blank to allow vertical comparison, as females do not sail the Laser

At Youth level no differences were observed in female or male classes. Mean overall physical fitness between Junior and Youth levels revealed greater differences between male Junior and Youth classes compared to the difference in females (Figure 7.4). In terms of percentile scores, female classes outperformed male classes at Junior level (47 ± 19 vs 38 ± 19%), with that trend reversing at Youth level (67 ± 16 vs 75 ± 14%). To enable direct comparison between the physical fitness of Optimist and Youth sailors in this study with previous research findings (Table 2.7 and Table 2.8) data is presented in Table 7.7.

Table 7.7 Physical fitness scores to enable comparison with previous research findings

		Optimist	Youth
Female	n	44	232
	Age (years)	13.1 ± 1.0	16.9 ± 0.9
	SLJ (m)	1.75 ± 0.16	1.81 ± 18
	20 m SRT (min)	9.6 ± 1.4*	9.2 ± 1.3*
Male	n	115	112 (Hike1)
	Age (years)	13.2 ± 0.9	17.4 ± 0.9
	SLJ (m)	1.76 ± 0.20	2.29 ± 0.19
	20 m SRT (min)	10.2 ± 1.6*	12.2 ± 1.2*

Note: * - 20 m SRT time is approximated from distance covered to allow comparison between studies

7.4 Discussion

This is the first study that has investigated anthropometrical, maturation and physical fitness characteristics in elite double-handed sailors and boardsailors below Olympic class level, plus it adds to the current limited amount of understanding in elite single-handed classes. This study revealed differences within Junior and Youth classes in anthropometry and maturation, with no differences found in physical fitness between classes at the same level. This result is in accordance with the hypothesis that there would be differences between the characteristics of Junior and Youth sailors competing in classes with varying physical demands.

7.4.1 Anthropometry

At Junior level both female and male Laser 4.7 class displayed the greatest height, mass and height x mass interaction, with differences observed with the smallest and lightest Optimist and Cadet Crew. A similar pattern emerged at Youth level with the female Laser Radial class displaying greater anthropometric qualities than the Hike2 classes, mirrored in the male Youth classes where the Laser and Laser Radial compared to the Hike2 classes. No differences were evident between the other pathway classes within level.

Within the limited previous research in elite Junior sailing, anthropometric markers have been recorded in elite Flemish and Italian female and male Optimist sailors (Callewaert *et al.,* 2014a; Callewaert *et al.,* 2014b; Lopez *et al.,* 2016). The current study measured greater numbers (44 females and 115 males) than previously investigated (less than ten in each study). In comparison to previous findings in a comparable age bracket (within a year), revealed similarities across most nations with Flemish males (Callewaert *et al.,* 2014a) appearing larger and Italian females smaller (Lopez *et al.,* 2016). The other study of elite pathway sailors included a combined group of 'dynamic' male Hike1 sailors (Laser 4.7, Europe and Laser Radial) (Callewaert *et al.,* 2014b). Anthropometrically these sailors (Age: 17.5 ± 1.0 years, height: 176.3 ± 4.8 cm, body mass: 72.0 ± 5.5 kg) fit within the range observed in the current study between Laser 4.7 and Laser Radial.

Elite Olympic class sailing has been reported to display distinct differences and specific anthropometry due to the differing physical and technical demands (Bojsen-Möller *et al.*, 2007; Bojsen-Möller *et al.*, 2014) which is corroborated in pathway sailing by Callewaert *et al.* (2014a) who stated that the dimensions of the Optimist encouraged optimal anthropometry to perform. The primary explanation of this relationship would be to examine the righting moment required to balance the force of the sails combined with the sailor to boat mass ratio (Table 7.1) to enable maximum boat speed (Evan, 2009; Mackie *et al.,* 1999). This relationship is simple in Hike1 and Board classes, though in double-handed classes the interaction of the crew may vary in bodymass, but also in class type between Hike2 or Trap, which may explain the lack of difference between double-handed classes. In hiking classes there are clear differences or trends towards greater anthropometry in response to greater sail area, for example Optimist vs. Laser 4.7 in males and females, Laser and Laser Radial vs. Laser 4.7 in males (Figure 7.1).

In elite Youth sailors anthropometry has been related to lab-based hiking performance in Laser sailors. Tan *et al.* (2006) cited the importance of body mass related to HM_{180} performance (r = 0.99 in females, 0.95 in male), height was only moderately correlated (r = 0.50 for females, 0.51 for males). This was hypothesised to be due to taller sailors having difficulty maintaining increased leverage from greater loads when attempting to maximise righting moment during hiking. Enhancing trunk strength/endurance would be recommended in hiking sailors make advantage of extra height and reduce injury risk.

It is important to note that anthropometrical characteristics will change through adolescence, so TDE programmes must take into account the individual non-linear trajectory of development especially accounting for periods of accelerated growth (Malina, 2004). Anthropometry should not be viewed as a predictor of success alone, as a standalone value may be viewed out of context against a long-term measure, such as predicted PAH, i.e. is the athlete tall because they are an early maturer or are they just in a higher percentile for height? TDE programmes must be aware that athletes will typically progress at different rates that could still ultimately end in success, and that strengths in some areas may compensate for weaknesses in others (Williams and Ericsson, 2005). If this process is to be attempted in an open sport such as sailing, the relative contribution of factors must be viewed in context of the number of factors that affect performance and development (Reilly *et al.,* 2000).

7.4.2 Maturation

In the current study female pathway sailors were generally estimated to be on-time or late maturers, with males in opposition on-time to early maturers, this became more pronounced with advancing age (Figure 7.2). Almost all Youth classes were estimated to be post-PHV plus the majority of female Junior classes (Figure 7.3). No difference was observed in predicted PAH in Junior classes (Table 7.3 and Table 7.4), though less difference would be more meaningful at Youth level (Table 7.5 and Table 7.6) as being closer to PAH especially with the majority being past periods of accelerated growth.

The only record of maturation status in previous sailing research was in Callewaert *et al.* (2014b), who found elite Optimist and older 'dynamic' hikers to be more advanced in maturation than non-elite counterparts: Optimist (elite: 2.2 ± 1.0, non-elite: 0.7 ± 0.8 years post-APHV), 'dynamic' hikers (elite: 3.0 ± 0.9, non-elite: 1.7 ± 1.1 years post-APHV). The maturity timing of female sailors in this study is in accordance with other sports, where elite female athletes have generally been found to be on-time or slightly later maturing with greater height and mass, though this is known to vary between sports (Baxter-Jones *et al.,* 2002).

The trend of male sailors in this study to be estimated to be on-time to early maturers corresponds with previous findings in other sports where selection bias towards more mature athletes have been reported in male sports where greater anthropometric and physical fitness impact performance (Gil *et al.,* 2007; Malina *et al.,* 2004; Meylan *et al.,* 2010; Mohamed *et al.,* 2009). Caution must be applied where it appears that there is a bias towards earlier maturing athletes, as later maturing athletes have been recorded to catch-up in physical development over time periods as short as two years (Till *et al.,* 2013a). This added to enhanced technical and non-physical abilities that may be developed from surviving competition with more physically proficient teammates/opposition (Gray and Plucker, 2010; MacNamara and Collins, 2011; Suppiah *et al.,* 2015) possibly resulting in more multi-skilled athletes (Vandendriessche *et al.,* 2012).

It is important to acknowledge that estimations of maturity status and timing include a degree of error, predominantly due to the individual variation in the tempo and timing of growth, especially around typical periods of accelerated growth (Beunen *et al.*, 1997; Khamis and Roche, 1975). This is relevant when comparing the current data with the UK 1990 reference standards (Freeman *et al.,* 1990).

7.4.3 Physical Fitness

No difference was observed in physical fitness in females or males within Junior or Youth classes (Table 7.3 to Table 7.6) though Youths outperformed Juniors in overall mean physical fitness score (Figure 7.4).

Previous research in physical fitness in elite pathway sailing has predominantly involved sailing-specific tests in Hike1 classes, revealing the importance of knee extensor and trunk strength and endurance (Burnett *et al.,* 2012; Callewaert *et al.,* 2014b*;* Tan *et al.,* 2006). In the context of TDE it is contended that physical fitness profiling should not include tests with a high sport-specific outcome, so that performance isn't biased to greater amounts of sport-specific training or time within the pathway system (Lidor *et al.,* 2009).

Non-specific physical characteristics have been shown to distinguish elite and non-elite sailors within and between performance level in Junior and Youth classes (Callewaert *et al.,* 2014b). Elite Optimist sailors outscored their non-elite counterparts in tests from the EUROFIT battery (Council of Europe, 1988) in motor co-ordination, while Youth dynamic hiking sailors displayed greater anaerobic and aerobic capacity. Aerobic capacity of Youth dynamic hiking sailors were comparable to elite football players (59.2 ± 3.2 mL·kg^{-1}·min^{-1}; Le Gall *et al.*, 2010) and greater than elite volleyball players (43 ± 6.1 mL·kg^{-1}·min^{-1}; Gabbett *et al.,* 2007). Previous findings in Junior and Youth-age groups are summarised in Table 2.7 and Table 2.8 respectively and can be directly compared to current data in Table 7.7. The results are in agreement as sailors in this study attained higher levels of aerobic fitness to a non-athletic sample at Junior and Youth age (females: 9.6 ± 1.4 vs. 4.6 ± 1.6 and 9.2 ± 1.3 vs. 4.5 ± 1.6 min respectively, males: 10.2 ± 1.6 vs. 6.6 ± 1.9 and 12.2 ± 1.2 vs. 8.2 ± 2.1 min respectively) (Deforche *et al.,* 2003) and similar to elite soccer players (U14: 9.5 ± 1.4 and U16: 11.2 ± 1.6 min) (Vaeyens *et al.,* 2006). Male Optimist sailors in this study outperformed the Flemish equivalent in aerobic fitness (10.2 ± 1.6 vs. 8.1 ± 0.8 min) (Callewaert *et al.,* 2014b) though were comparable in other measures at an older level (12.2 ± 1.2 vs. 11.1 ± 1.4 min).

The lack of difference in SLJ performance in elite Junior and Youth Hike1 sailors in this study compared to a non-athletic population (females: 1.75 +_ 0.16 vs. 1.61 ± 0.18 and 1.81 ± 0.18 vs. 1.67 ± 0.21 m respectively, males: 1.76 ± 0.20 vs. 1.75 ± 0.19 and 2.29 ± 0.19 vs. 2.11 ± 0.22 m respectively) (Deforche *et al.,* 2003) may conflict with previous research that reported greater levels of strength in knee extensor muscles in Youth sailors (Burnett *et al.,* 2012; Callewaert *et al.,* 2014b; Tan *et al.,* 2006) as jumping involves a large contribution from the same musculature. Though it is in line with Callewaert *et al.* (2013b) that found similar levels of knee extensor MVC in elite Optimist sailors versus non-trained age-matched control (151 ± 43.9 vs. 155.3 ± 55.3 Nm), the greater strength in previous research may have been due to the sailing-specific nature of testing applied in older elite athletes who have had access to a higher cumulative volume of sailing training, limiting the application of these tests from a TDE perspective in sailing.

Variation in physical fitness measured within classes at Junior level may be caused by varying timing and magnitude of maturation (Malina *et al.,* 2004) although almost all female classes and most Youth classes were estimated to be post-PHV which would have reduced the impact of maturity timing. Elite sailing is a complex sport that requires the combination of many factors including: decision-making, cognitive function, tactics, boat design and skill (Bojsen-Möller *et al.*, 2007; Sjøgaard *et al.,* 2015) therefore it can be expected that a range of physical characteristics at pathway level may exist within classes.

Physical differences between classes at Olympic level have been reported to be due to the differing physical and technical demands (Bojsen-Möller *et al.*, 2007; Bojsen-Möller *et al.*, 2014). Differences were not observed in this study, which potentially highlights a reduced variation in the physical and technical demands, in support of this Chapter 3 displays athletes and coaches comments on the step up in physicality when transitioning into Olympic sailing though this may be class-specific. Another possible explanation of the lack of physical fitness differences between classes are the use of tests that are dependent on anthropometric profile i.e. body weight tests of jumps and running versus RM-testing or cycling which may disadvantage sailors with greater body mass. At Olympic level the forces created by sailors in different classes were not as different when made relative to individual MVCs as larger sailors created greater force (Mackie *et al.,* 1999). It must be highlighted that details of sailing training volume and participation in other sports were not recorded, therefore fitness scores may be impacted through volume of physical training.

7.5 Practical applications

Differences in anthropometry and maturation were observed in Olympic pathway sailors, however no difference was reported in physical fitness at Junior or Youth level. It is clear that to support the selection of elite sailors that maturation status must be acknowledged where classes display distinct anthropometrical characteristics, to avoid selection bias to sailors advanced in maturation status. Due to the differences in maturity timing observed between female and male sailors at Junior level, it is recommended that greater awareness of gender differences are promoted to impact development at that level while accounting for individual variation.

Younger athletes should be profiled against a range of movements/abilities as these relate to developing robustness to cope with the increasing demands of the sport (Lloyd *et al.,* 2015b). In sailing this is particularly relevant as sailors have a number of possible trajectories available to them as they progress up the Olympic pathway across a range of class types (Figure 1.10). It is important to support the inclusion of non-specific tests in the Olympic pathway lie in the uncertainty of the Olympic classes that will exist when pathway sailors reach adulthood. As can be seen in Figure 1.6, the Olympic classes may change every four-year cycle, possibly rendering previous specific test data meaningless.

The current study analyses the physical characteristics of elite sailors at Junior and Youth level using a cross-sectional approach over the 2012-2017 time period. In line with previous conclusions in talent research, there are limitations with cross-sectional designs only providing a snap shot of ability discounting the individual variation of development (Philippaerts *et al.,* 2006; Till *et al.,* 2013a; Vaeyens *et al.,* 2008). Therefore to increase the understanding of physical development in the Olympic pathway the next study will analyse longitudinal individual trajectories of sailors who transitioned from elite Junior to Youth level, to further this understanding, development will be compared to the age-matched elite population.

Chapter 8 An individual case study approach to analyse longitudinal anthropometric and physical fitness developments in elite Youth sailors over a three-season period.

8.1 Introduction

Previous research in the area of elite sport pathways has revealed varying levels of effectiveness of 'talent pathways' to produce future adult elite participation and success (see section 2.3). No single ideal pathway trajectory has been observed across a number of sport, challenging the conception of elite linear single-sport journeys (Gulbin *et al.*, 2013; Güllich and Emrich, 2012; Güllich and Emrich, 2014). In fact, separate studies who investigated the journeys of large samples of elite sportspeople across a range of sports reported less than 7% (n = 256) experienced a pure linear journey (Gulbin *et al.,* 2013) and very strong correlation between younger entry into a TID pathway with early exit (r = 0.92, n = 4,686) (Güllich and Emrich, 2012).

In an attempt to assess the effectiveness of the British Sailing Team pathway an analysis of 26 recent top sailing performers competing since 2004 was conducted (unpublished). Sailors were chosen by holding a minimum of a top two world ranking, including 16 Olympic medallists and 25 World Championship medallists. Results showed 88% were members of both British Sailing elite Junior and Youth squads, 96% participated in elite Youth squads. This highlights the importance of participation at Junior, but more importantly at Youth level in the Olympic pathway in sailors who achieved success at elite adult level. Based on this knowledge, understanding the developmental journey of sailors achieving elite Youth squad status is important to aid the support that can be given in the TDE environment.

In an attempt to gain more understanding of young athlete development within sporting pathways, programmes and professional teams have included the assessment of a number of physical characteristics including: anthropometry (height, body mass and body composition) motor skills (e.g. balance, co-ordination, and agility) and physical fitness (e.g. aerobic fitness, strength and speed) (Lidor *et al.,* 2009). Tracking these physical characteristics provides objective scientific data to work alongside the subjective coach assessment of current ability and/or potential (Abbott *et al.,* 2002) and provides further information on athletic development relevant to future sport-specific skill development (Williams and Reilly, 2000).

No research to date has investigated the longitudinal physical development of elite sailors. A few studies using cross-sectional designs have identified differences in physical characteristics between performance level and age, predominantly in males and in a limited selection of Hike1 classes (Burnett *et al.,* 2012; Callewaert *et al.,* 2013a, 2013b, 2014a, 2014b; Lopez *et al.,* 2016; Tan *et al.,* 2006). The findings from the previous chapter have strengthened the understanding of anthropometrical, maturation and physical characteristics across all Junior and Youth classes in both genders using a battery of tests specific to sailing, confirmed through understanding of key physical characteristic development in successful elite sailors (Chapter 3). This data provides a set of normative values that may be used to track sailors against longitudinally that can aid selection, inform training prescription and help monitor progression (Lidor *et al.*, 2009).

Numerous studies have investigated physical characteristics in young athletes across other sports and their interaction with performance level typically using cross-sectional designs differentiating between elite and non-elite athletes at particular stages (Falk *et al.,* 2004; Matthys *et al.*, 2013a; Mohamed *et al.,* 2009; Moss *et al.,* 2015; Reilly *et al.,* 2000; Vaeyens *et al.,* 2006), between stages (Lawton *et al.,* 2012; Lloyd *et al.,* 2015c López-Plaza *et al.*, 2016; Till *et al.,* 2013a; Vaeyens *et al.,* 2006; Vandendriessche *et al.,* 2012), and supporting future elite participation (Table 2.2). Not all studies have shown a significant interaction (Franks *et al.,* 1999; Elferink-Gemser *et al.,* 2004) which isn't surprising due to the complex multi-factorial nature of TDE and performance (MacNamara and Collins, 2011; Suppiah *et al.,* 2015).

Proficiency in physical characteristics during TDE has been shown to underpin progression through developing a solid foundation of fundamental movement skills as displayed in the YPD and CYD models (Lloyd *et al.,* 2015c) leading to development of AMSC (Moody *et al.,* 2013). These abilities provide a basis to progress skill (Gulbin, 2008) and perform sport-specific tasks with confidence and optimal technique (Bergeron *et al.,* 2015). A number of authors have highlighted the benefit of physical capacity to enhance the quality and effectiveness of deliberate practice (Elferink-Gemser *et al.,* 2010; Kliegl *et al.,* 1989). Increased strength and conditioning is linked to reducing injury risk (Myer *et al.,* 2013) as much as 1/3 to 1/2 of acute and overuse injuries respectively (Lauersen *et al.,* 2014). Physical robustness assists preparation for the increased demands of high volumes of sport-specific training and competition at higher levels of performance (Lloyd *et al.,* 2015b) and can also improve self-esteem and wellbeing (Lloyd *et al.,* 2012). Due to these research findings it would be advised to obtain and analyse regular physical profiles of developing athletes, in continuation of this Vaeyens *et al.* (2008) contend that successful elite athletes will require a minimum competence across a range of characteristics, therefore furthering understanding in this area will aid the effectiveness of the pathway through benchmarking development.

The impact of physical characteristics will vary based on the specific sport, as more open sports rely on a greater number of factors for development and performance (Reilly *et al.,* 2000), and also on the individual athlete. As the non-linear trajectory explained in previous research will vary between individuals, typically from differences in maturity (Malina *et al.,* 2004) and various compensatory mechanisms (Williams and Ericsson, 2005). The uncertainty of these factors strengthen the case for the tracking of physical characteristics longitudinally accounting for maturation towards development of athletes rather than prediction of future success. For a more detailed review on the effects of physical characteristics on TID and TDE refer to sections 2.3 and 2.4).

Longitudinal research investigating the physical development is less common, but necessary to encapsulate the variation in individual development (Till *et al.,* 2013a; Till *et al.,* 2013b; Vaeyens *et al.,* 2008). Differences in the trajectory of physical characteristics have been observed in talent identified rugby league players, Till *et al.* (2013a) followed TID rugby league players longitudinally from U13 to U15 stages, grouping the players into early, on-time and late maturers. Early maturing players were advanced in anthropometrical measures (height ($P < 0.001$, $\eta^2 = 0.498$), sitting height ($P < 0.001$, $\eta^2 = 0.658$) and body mass ($P < 0.001$, $\eta^2 = 0.388$)) and upper body power ($P < 0.001$, $\eta^2 = 0.273$) in all three testing years. Significant differences were observed between maturation groups over the three testing sessions (maturation group x time interaction – $F_{60, 98} = 2.101$, $P = 0.01$, $\eta^2 = 0.563$) revealing that the later maturing group increased in a range of anthropometrical (height, sitting height, body composition) and physical measures (upper body power and speed) at a faster rate than the more biologically advanced groups indicating a 'catch-up effect'. Till and colleagues (2013b) followed this study up by tracking three players in a case study approach over the three-year period using population-based cross-sectional values as a standard to compare against. This analysis revealed large variations in physical characteristics and in progression across a range of playing positions, thus advocating long term assessments focusing on individuals using cross-sectional data to track development against.

In another longitudinal study, Philippaerts and colleagues (2006) investigated the development of football players within the Ghent Youth Soccer Project for five years, starting at 10.7 – 13.7 years old, in a range of physical characteristics. Measurements of maturation status were taken once a year, but determined over half-year intervals using non-smoothed polynomials. All physical values (Balance, agility, strength, speed, aerobic capacity, trunk strength and explosive strength) increased within the five year period, with most increasing at the greatest rate around APHV. Increases in physical performance around APHV and the period post-APHV have been attributed to the development of muscle mass (Malina *et al.*, 2004) and possibly the interaction of physical training organised through the sport. To highlight the variance in physical development through maturation Pearson *et al.* (2006) summarised the effects of puberty on physical characteristics (Table 8.1). Plateaus in development were observed post-APHV in upper body strength, lower body power and speed which highlight the need for repeated assessments rather than one-off snap-shot testing for selection (Abbotts and Collins, 2004). The authors noted that individual differences were observed in timing and magnitude of growth which would require an understanding of the physical relationship with growth when programming training and initiating a selection process. Crucial to this process is awareness of the difference between chronological and biological age (Figure 8.1) when benchmarking development and prescribing training interventions (Lloyd *et al.,* 2014).

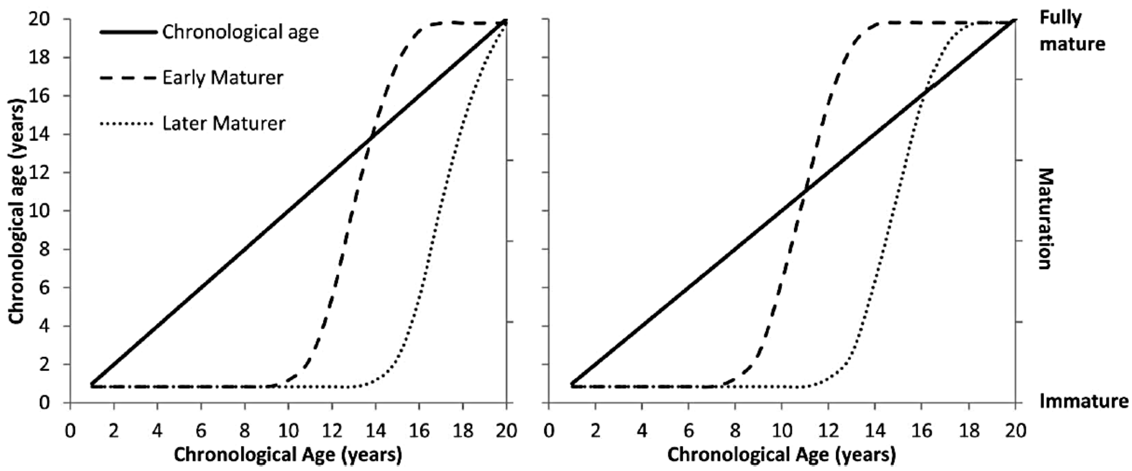

Figure 8.1 Theoretical chronological and biological age developmental trajectories in males (left) and females (right), taken from Lloyd *et al.* (2014).

The aims of this study were twofold, firstly to longitudinally investigate individual anthropometric and physical fitness characteristics in two elite female and male sailors prior to and during transition into Youth class sailing based on cross-sectional age-matched population means. Secondly, to analyse and compare the variation observed within this transition between individual sailors using chronological and biological age to benchmark progression.

Table 8.1 Effect of puberty on physical characteristics (redrawn from Pearson et al., 2006)

Characteristic	Effect of puberty	Approximate change during puberty	Age at greatest increase (years)	Trainability	Hormone mediated
Height	Increase in height	↑ 17—18%	13.5	No	Yes
Weight	Increase in total body mass	↑ 40%	13.5	Yes	Yes
Muscular development	Increase in muscle mass	↑ 20%	13.5	Yes	Yes
Body fat	Increase of total fat (small decrease in % body fat at age 14—16 years)	↑ 50% (%body fat)	Steady increase	Yes	Yes
$\dot{V}O_2$ peak ($L \cdot min^{-1}$)	Steady increase throughout adolescence related to increased FFM and improved cardiovascular system	↑ 70%	12—13	Yes	Yes
$\dot{V}O_2$ peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	Small decrease during early adolescence, but remaining steady during later adolescence	Steady	NA	Yes	No
Anaerobic power	Steady increase in childhood, with a rapid increase during puberty	↑ 50%	14—16	Yes	Mostly
Anaerobic capacity	Steady increase throughout adolescence	↑ 200%	Unknown	Yes	Yes
Strength	Dramatic increase associated with body size	↑ 150%	14—16	Yes	Yes
Skill	Increase during adolescence related to practice and possibly increased physical ability	Dependent on type of skill	Unknown	Yes	Partially
Agility	Possible increase during adolescence	↑ 20%	Unknown	Probably	Partially

8.2 Methods

8.2.1 Participants

The sailors described in this longitudinal case study design were selected from the initial five year period of a longer-term data collection project within British Sailing to track the physical characteristics of Olympic sailors. Participants comprised of two female and two male elite Youth sailors who were tested at physical profiling sessions for three seasons within 2013/4 to 2016/7 period after the introduction of Press-up and Supine Pull tests for upper body push and pull strength respectively.

The four sailors selected for this study consisted of: female group - sailor one (F1: age 13.2 to 15.5 years), class trajectory included Topper, Laser 4.7 and Laser Radial at Youth level (all Hike1 positions), sailor two (F2: 15.4 to 17.6 years) class trajectory included 29er helm only (Hike2) from transition to Youth level. In male group – sailor one (M1: 14.7 to 17.0 years) class trajectory included Laser 4.7 and Laser Radial at transition and Youth level (Hike1), sailor two (M2: 14.4 to 16.7 years) class trajectory included Optimist and 420 helm at transitional and Youth level (Hike1 and Hike2). Sailors were selected with a deliberate bias to include a range of age, class type and maturation status – choosing an earlier and later-maturing sailor within each gender. This was conducted to evidence the magnitude of possible variation between sailors' trajectories across different timings of maturity through adolescence. All sailors were of UK Caucasian descent. This study was approved via the ethics committee of the University of Chichester. Informed consent was received from parents and sailors as part of acceptance of a place within the Olympic pathway and/or attendance at physical profiling sessions.

8.2.2 Procedures

Measurements were collected at up to six time points per sailor (two per season: September to March) for the two seasons preceding transition (T-4, T-3, T-2, T-1), at transition (T), and finally one date corresponding with the next possible deselection point (T+1) confirming 'survival' within the elite squad (0.3 to 0.6 years post-transition). In some cases data is missing due to non-attendance at profiling session or through restriction of tests through injury.

Maturation assessments were completed as described in section 7.2.2 from the outcome of Chapter 6, with the addition of the estimation of biological age (BA), which was achieved through comparing %PAH (Khamis and Roche, 1995) of the sailor with age and gender-matched data from the UK 1990 growth reference standards calculated in 0.1 year intervals (Freeman *et al.,* 1990). For example: a male sailor who had reached 90%PAH would have an equivalent age (BA) of 13.7 years when compared to the mean %PAH attained by males within the UK 1990 reference data.

For detailed explanations of procedures completed within this study please see Chapter 4 (anthropometry, T-test, SLJ, 20 m SRT), section 5.2.2 (Press-ups and Supine pulls) and section 6.2.2 (predicted PAH). Pre-reading for sailors outlining the procedures and information on pre-testing preparation can be found in Appendix 7.

8.2.3 Data Analysis

Analysis of longitudinal sailor data was completed using descriptive statistics, presented visually using tables and graphs plotted over time. To compare individual sailor scores longitudinally against CA and BA-matched population, z-scores were calculated in using the formula z = $\bar{x}$ – (μ/σ) where $\bar{x}$ is raw score, μ is the mean of population, and σ is the S.D. of the population. A zero z-score reflects the mean of the population, with deviation reported to two decimal places. Population information was collated from female and male physical profiling scores over five years with data separated into specific 0.5 year age groups i.e. 12.250 to 12.749 years = 12.5 year group, 12.750 to 13.249 years = 13.0 year group.

All anthropometrical and maturation data are presented as raw data, physical test scores are presented in raw form with a combined overall physical fitness score as a percentile. Percentiles were calculated from the range of scores performed in tests over the five year period, with the best female/male score in each test representing 100%, and the worst 0%. Statistics all displayed as means ± S.D. unless noted otherwise.

8.3 Results

Table 8.2 and Table 8.4 display maturation, anthropometric and physical fitness characteristics of two female and two male elite Youth sailors pre-, during- and post-Transition (T) to elite Youth squad measured in six approximately half-yearly time points. Table 8.3 and Table 8.5 show the raw change between time points i.e. T-4 – T-3, T-3 – T-2, T-2 – T-1, T-1 Figure 8.2 and Figure 8.3 display the individual sailors' trajectories within gender over the approximately three season period relative to the age-matched z-scores for the elite sailing population. Results are also reported in context to class values displayed in the previous study (Table 7.3 to Table 7.6).

8.3.1 Female sailors

Both female sailors were estimated to be post-PHV throughout the study time period. Sailors began the study categorised as slightly-early (F1) and late-maturing (F2). A negative drift was observed in z-scores over the study duration resulting in F1 recorded as 'on-time' at T+1. Sailors' chronological ages differed by approximately two years, due to differences in maturation status sailors were almost identical in %PAH at T (99.4 and 99.4%) and T+1 (99.5 and 99.7%), representing similar BA (<0.3 years difference).

F1: Youngest of the female sailors (14.2 years) and least mature (97.2% PAH) at T-4 although slightly early in maturation status (z-score 0.6). In Topper and Laser 4.7 classes anthropometric characteristics were near average (height x mass: 87 vs. 92 ± 12 and 100 vs. 103 ± 9) whereas in Laser Radial on the lower end as height only increased 3 cm from T-4 to T+1, even though bodymass increased by 11.8 kg to 65.5 kg (Laser Radial bodymass: 68.6 ± 5.6 kg). At T-4, F1 was low in physical fitness (23%) versus Junior mean (47 ± 19%), though made large improvements (+50%) ending above mean values reported in Youth (73 vs. 67 ± 16%) and relative to BA-matched population mean (z-score +0.87). F1 recorded large increases in performance in T-test (-0.94 sec) and SLJ (0.39m) compared to F2. The largest period of improvements relative to age-matched population occurred from T-4 to T-2 (13.2 – 14.3 years), from T-4, F1 began below the mean (z-score -1.78) with greatest increases seen in press-ups (1.92), supine pulls (1.53) and SLJ (2.42) resulting in an overall increase of 2.65.

F2: Older of two sailors (15.2 years) and most mature (98.3% PAH) at T-4, though remained a late maturer throughout (z-score range: -1.0 to -2.2). F2 was consistently close to the class means for position in anthropometry measured by height x mass from 89 to 96 versus 29er helm range of 93 ± 8. This was evidenced in raw scores through minimal change of 0.7 cm and 2.7 kg in height and bodymass over three seasons respectively. At T-4, F2 was at the lower end of physical fitness for elite Youth sailors (53 vs. 67 ± 16%) though progressed to 86% resulting in a z-score of 1.15 above the age-matched population mean and greatest of the female sailors in this study. F2 exhibited the greatest variation in physical fitness characteristics, repeatedly rising and dropping over a z-score of 0.5 within each season, with improvements corresponding to the end of Winter training period and losses in fitness relating to the summer competition period (Winter – Summer change: +22, -11, +13, -7, +16%).

In summary, F1 was the youngest sailor with largest increase in anthropometry and maturation over three seasons. Also greatest improvements in physical fitness, starting from the lowest level. F2 exhibited the smallest change in anthropometry and maturation and oldest sailor, observed the largest variation in physical fitness scores apart from F1 (T-4 to T-2). Although F2 was a later maturer, due to her greater starting age went through less change in maturity BA (1.0 vs. 1.7 years) and %PAH (0.8 vs. 2.3%) compared to F2, possibly highlighting a potential factor to explain the lesser increases in overall physical fitness (33 vs. 50%).

Table 8.2 Anthropometric and Physical fitness characteristics of two individual female sailors pre-, during-, post-Transition (T) to elite Youth squad

Female	F1						F2					
	T-4	T-3	T-2	T-1	T	T+1	T-4	T-3	T-2	T-1	T	T+1
Class	Topper	Topper	Laser 4.7	Laser 4.7	Radial	Radial	29er	29er	29er	29er	29er	29er
Level	JUNIOR	JUNIOR	JUNIOR	JUNIOR	YOUTH	YOUTH	TT	TT	TT	TT	YOUTH	YOUTH
Type	Hike1	Hike1	Hike1	Hike1	Hike1	Hike1	Hike2	Hike2	Hike2	Hike2	Hike2	Hike2
Age (years)	13.2	13.7	14.3	14.5	15.2	15.5	15.4	15.7	16.4	16.6	17.1	17.6
Biological age (years)	13.8	14.3	14.9	15.0	15.4	15.5	14.8	14.8	15.2	15.2	15.3	15.8
Maturation (z-score)	0.6	0.5	0.3	0.4	0.2	0.0	-1.4	-1.2	-1.4	-1.5	-2.2	-1.0
%PAH (%)	97.2	98.0	99.0	99.1	99.4	99.5	98.3	99.0	99.3	99.3	99.4	99.7
Height (cm)	162.5	164.3	164.3	165.2	165.2	165.5	168.4	167.7	168.7	168.5	168.8	169.1
Mass (kg)	53.7	55.0	61.0	61.3	65.1	65.5	53.7	56.1	57.0	56.5	56.5	56.4
Height x mass	87	90	100	101	108	108	90	94	96	95	95	95
T-test (sec)	12.96	-	13.00	12.65	11.89	12.02	11.23	11.03	12.35	11.81	12.19	11.49
SLJ (m)	1.44	1.43	1.70	1.76	1.74	1.83	1.70	1.73	1.71	1.84	1.78	1.83
Press-ups (reps)	2	3	2	7	13	18	0	4	3	3	9	16
Supine Pulls (reps)	3	13	15	12	15	19	10	20	20	20	20	22
Bleep Test (m)	1220	-	1500	1280	1280	1280	1420	1540	1600	1680	1380	1580
Overall Fitness (%)	23	-	67	54	63	73	53	75	63	76	69	86

Table 8.3 Raw change in maturation, anthropometric and Physical fitness characteristics of individual female sailors over three-year period across elite Youth squad transition (T)

Female	F1						F2					
	T-4 - T-3	T-3 - T-2	T-2 - T-1	T-1 - T	T - T+1	T-4 - T+1	T-4 - T-3	T-3 - T-2	T-2 - T-1	T-1 - T	T - T+1	T-4 - T+1
Age (years)	0.4	0.6	0.3	0.7	0.3	2.3	0.2	0.8	0.2	0.5	0.4	2.1
Biological age (years)	0.4	0.7	0.1	0.4	0.1	1.7	0.1	0.3	0.0	0.2	0.4	1.0
%PAH (%)	0.8	1.0	0.1	0.3	0.1	2.3	0.1	0.3	0.0	0.1	0.3	0.8
Height (cm)	1.8	0.0	0.9	0.0	0.3	3.0	0.3	1.0	-0.2	0.3	0.3	0.7
Mass (kg)	1.3	6.0	0.3	3.8	0.4	11.9	2.4	1.0	-0.5	0.0	-0.1	2.7
T-test (sec)	-	-	-0.35	-0.76	0.13	-0.94	-0.20	1.32	-0.54	0.38	-0.70	0.26
SLJ (m)	-0.01	0.27	0.06	-0.02	0.09	0.39	0.03	-0.02	0.13	-0.06	0.05	0.13
Press-ups (reps)	1	-1	5	6	5	16	4	-1	0	6	7	16
Supine Pulls (reps)	10	2	-3	3	4	16	10	0	0	0	2	12
Bleep Test (m)	-	-	-220	0	0	60	120	60	80	-	200	160
Overall Fitness (%)	-	-	-13	9	10	50	22	-11	13	-7	16	33

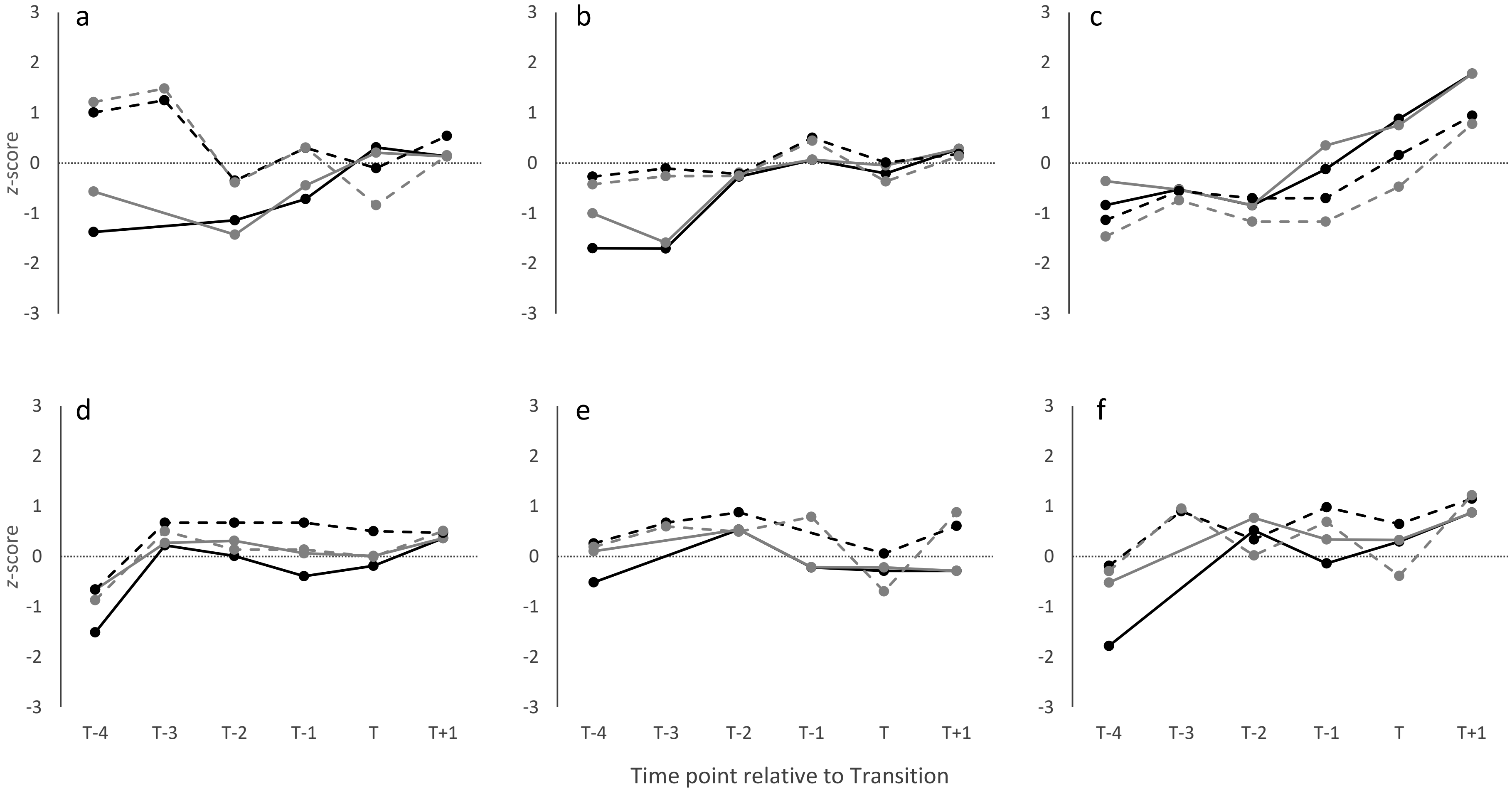

Figure 8.2 z-score change in female Physical fitness characteristics over thee-year period across elite Youth squad transition (T) compared to BA-specific mean. Note: Solid line – F1, dotted line – F2, grey lines – CA, black lines – BA, a -T-test, b - SLJ, c - Press-ups, d - Supine Pulls, e - Bleep test, f - Overall%

8.3.2 Male sailors

Greater variation in maturation was observed in males compared to females in ages relative to PHV, with one of the male sailors estimated to be pre- and circa-PHV during the three season period. However, maturation status was more stable over time with sailors remaining in the same categories: M1 slightly early (z-score range: 0.7 to 0.9) and M2 late (-2.0 to -1.0). Chronological ages were similar between sailors (<0.3 years at T-4), representing variation in BA within male sailors in this study.

M1: Oldest at T-4 (14.7 years) and most mature throughout the study period (96.1 to 99.8% PAH). In Laser 4.7 M1 possessed greater anthropometric characteristics than the class mean plus S.D. (height x mass: 114 and 116 vs. 100 ± 11), close to class mean in Laser Radial (128 -131 vs. 129 ± 9). Over the study period M1 increased height by 7.3 cm, with 4.6 cm T-4 to T-3, and bodymass by approximately 2 kg per year peaking at 5.6 kg rise in 0.8 years from T-3 to T-2. Physical fitness remained above the mean for Junior and Youth (45 to 48 vs. 38 ± 19% at Junior and 77 to 84 vs. 75 ± 14% at Youth), with an overall increase of 41%. The greatest period of improvement was T-3 to T-1 with 25% rise in 1.0 years, notable gains over this time period included -1.41 sec in T-test and 880m further in bleep test. Relative to BA-matched population, M1 possessed a very high bleep test score (z-score 2.69), from T-2 to T+1 improvement was above the rate of population mean, overall physical fitness scores remained below the mean until T, ending slightly above mean with z-score of 0.42 at T+1.

M2: Similar age to the other male sailor (14.4 years) at T-4, and the least mature throughout the study period (84.9 – 95.7% PAH), spanning the age period pre-, circa- and post-PHV unsurprisingly associated with the greatest increase in maturation (10.8% PAH). At T-4 , M2 was on the lower end of Optimist class in anthropometrical characteristics (height x mass: 57 vs. 67 ± 13), even though growing 16.7 cm over three seasons remained small as 420 helm (73 to 85 vs. 104 ± 12). M2 sharply increased height during T-4 to T-2 (10 cm over 1.2 years), with steady increases of 4 – 6 cm per year from T-2 to T+1. Two sharp increases in bodymass from T-4 to T-2 (7.2 kg in 1.2 years) and T-1 to T (2.8 kg in 0.5 years). At T-4, M2 displayed a low level of physical fitness relative to Junior level (21 vs. 38 ± 19%) though not as apparent against BA-matched population (z-score -0.22). M2 made large increases (41%) in physical fitness including a particular spike of 20% from T1-T (0.5 years) corresponding with increase in bodymass (5.6 kg per year). Continuous improvements were made in physical fitness, M2 improved greater than the rate of population mean from T-3 to T, peaking at absolute z-score of 0.78, finishing at 0.61.

In summary, M1 was most mature and older, made large improvements early in study period with continued improvement above rate of population mean through Youth transition, ending slightly above the population mean. M2 was least mature at the start of measurement though recorded greater increase in %PAH. Made large increases in anthropometry and physical fitness characteristics, especially in T-4 to T period pre- and circa-PHV. Shorter in stature, and progressed at greater rate to BA-matched population mean in physical fitness.

Table 8.4 Anthropometric and Physical fitness characteristics of two individual male sailors pre-, during-, post-Transition (T) to elite Youth squad

Male	M1						M2					
	T-4	T-3	T-2	T-1	T	T+1	T-4	T-3	T-2	T-1	T	T+1
Class	Laser 4.7	Laser 4.7	Radial	Radial	Radial	Radial	Optimist	-	420	420	420	420
Level	JUNIOR	JUNIOR	TT	TT	YOUTH	YOUTH	JUNIOR	-	TT	TT	YOUTH	YOUTH
Type	Hike1	Hike1	Hike1	Hike1	Hike1	Hike1	Hike1	-	Hike2	Hike2	Hike2	Hike2
Age (years)	14.7	15.1	15.9	16.1	16.7	17.0	14.4	-	15.6	15.8	16.3	16.7
Biological age (years)	15.3	15.8	16.9	16.9	17.5	18.0	12.3	-	13.8	14.3	15.0	15.2
Maturation (z-score)	0.9	0.7	0.7	0.7	0.7	0.7	-2.0	-	-1.6	-1.5	-1.2	-1.1
%PAH (%)	96.1	97.4	99.0	99.1	99.5	99.8	84.9	-	90.8	92.9	95.4	95.7
Height (cm)	177.9	179.9	182.5	183.0	184.3	185.2	150.5	-	160.5	162.1	164.9	167.2
Mass (kg)	64.0	64.7	70.3	69.5	69.7	70.5	38.2	-	45.4	46.1	48.9	50.8
Height x mass	114	116	128	127	128	131	57	-	73	75	81	85
T-test (sec)	11.56	12.23	11.30	10.82	10.83	10.55	11.78	-	11.49	11.38	10.73	10.55
SLJ (m)	1.93	2.04	1.88	2.01	2.26	2.23	1.56	-	1.80	1.70	1.87	1.85
Press-ups (reps)	13	12	21	24	27	25	2	-	8	9	22	19
Supine Pulls (reps)	14	23	20	22	18	28	6	-	16	29	30	25
Bleep Test (m)	1940	1840	2340	2720	2360	2360	1880	-	1760	1900	2060	1980
Overall Fitness (%)	45	48	61	73	77	84	21	-	37	48	68	65

Table 8.5 Raw change in maturation, anthropometric and Physical fitness characteristics of individual male sailors over three-year period across elite Youth squad transition (T)

Male	M1						M2					
	T-4 - T-3	T-3 - T-2	T-2 - T-1	T-1 - T	T - T+1	T-4 - T+1	T-4 - T-3	T-3 - T-2	T-2 - T-1	T-1 - T	T - T+1	T-4 - T+1
Age (years)	0.3	0.9	0.2	0.6	0.3	2.3	-	-	0.2	0.5	0.4	2.3
Biological age (years)	0.6	1.1	0.0	0.6	0.5	2.8	-	-	0.5	0.7	0.2	2.8
%PAH (%)	1.3	1.6	0.1	0.4	0.3	3.7	-	-	2.1	2.5	0.3	10.8
Height (cm)	2.0	2.6	0.5	1.3	0.9	7.3	-	-	1.6	2.8	2.3	16.7
Mass (kg)	0.8	5.6	-0.8	0.2	0.8	6.6	-	-	0.7	2.8	1.9	12.6
T-test (sec)	0.67	-0.93	-0.48	0.01	-0.28	-1.01	-	-	-0.11	-0.65	-0.18	-1.23
SLJ (m)	0.11	-0.16	0.13	0.25	-0.03	0.30	-	-	-0.10	0.17	-0.02	0.29
Press-ups (reps)	-1	9	3	3	-2	12	-	-	1	13	-3	17
Supine Pulls (reps)	9	-3	2	-4	10	14	-	-	13	-9	-5	14
Bleep Test (m)	-100	500	380	-360	0	420	-	-	140	160	-80	100
Overall Fitness (%)	3	13	12	4	7	39	-	-	11	20	-3	41

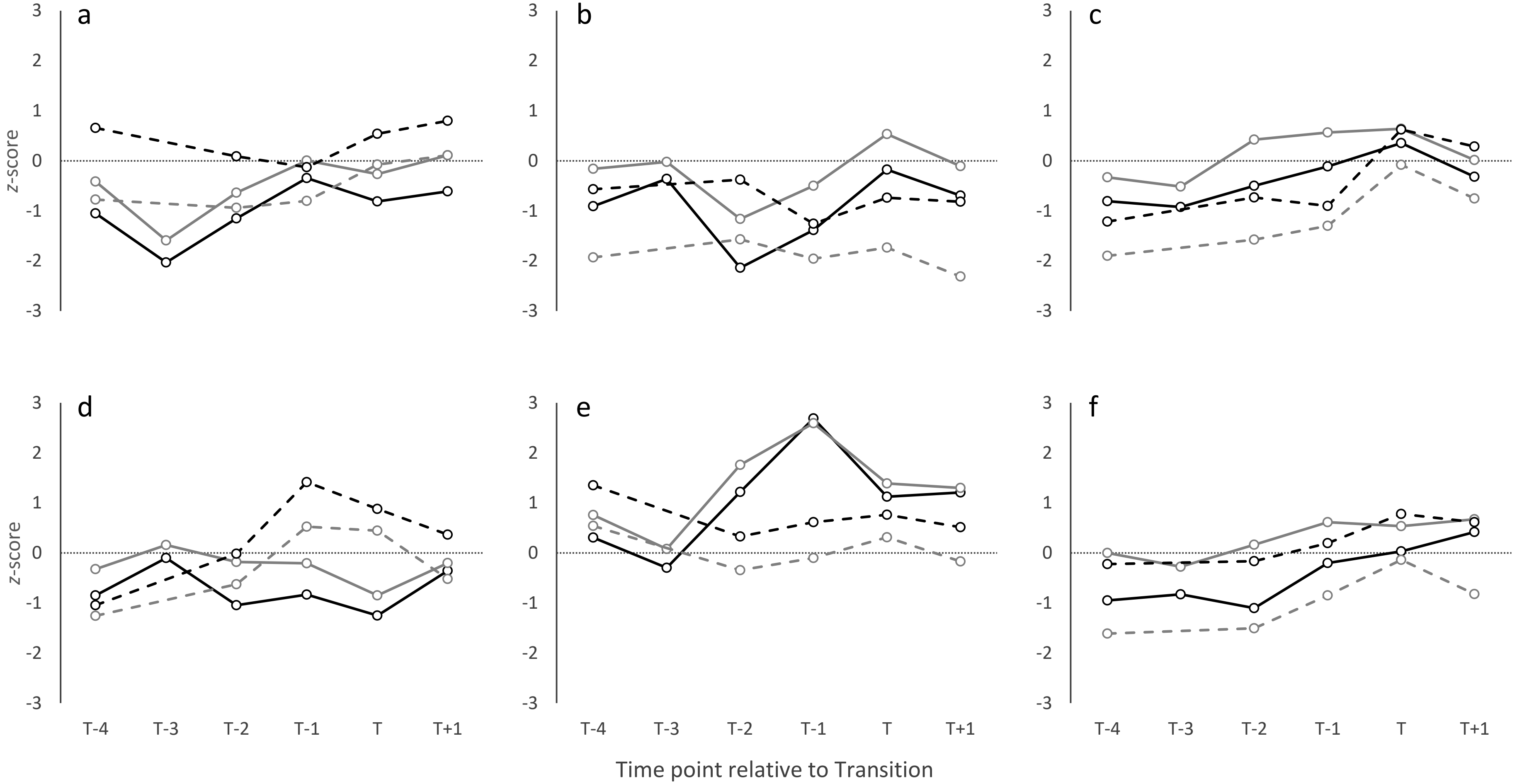

Figure 8.3 z-score change in male Physical fitness characteristics over thee-year period across elite Youth squad transition (T) compared to BA-specific mean. Note: Solid line – M1, dotted line – M2, grey lines – CA, black lines – BA, a -T-test, b - SLJ, c - Press-ups, d - Supine Pulls, e - Bleep test, f - Overall%

8.3.3 CA versus BA-matched comparison

The impact of different age-matching categories (CA vs. BA) varied between genders and sailors. In male sailors the pattern was consistent, with M1 (earlier maturing) displaying lower scores relative to BA-matched population versus chronological with the opposite evident in M2 (later maturing) scoring higher when relative to BA. The magnitude of this difference was greater in M2 (z-score difference 0.4 to 1.81 vs. 0.07 – 1.27) in line with greater age gap between BA and CA (-1.5 to -2.1 vs. 0.6 to 1.0 years). The trend in female sailors was less clear, with non-consistent pattern of CA versus BA-matched z-scores, though clear disparity was evident in F1 at T-4 (BA-CA z-score difference: -0.5 to -1.39) and T in F2 (0.45 to 1.12). Across sailors of both genders, the effect of comparing to BA-matched benchmarks from CA results in z-scores changing from over to under mean values.

8.4 Discussion

The aims of this study were to longitudinally investigate individual anthropometric and physical fitness characteristics in elite female and male sailors prior to and during transition into Youth class sailing based on cross-sectional age-matched population means, and to compare variation observed within this transition using CA versus BA to benchmark progression. This study progressed the experimental design utilised by Till *et al.* (2013b) where an individual case study approach was used longitudinally in elite Rugby League players to assess the dynamic inter-individual variation through adolescence. The findings within this study of large variation in magnitude and timing of physical development are in line with previous longitudinal research (Philippaerts *et al.,* 2006; Till *et al.,*2013a; Till *et al.,* 2013b), plus offer new recommendations based on BA tracking in elite athlete pathways. These findings are discussed in more detail in this section:

Large variation was observed within and between female and male sailors' anthropometry and physical fitness that can be seen in Table 8.3 and Table 8.5. In raw scores the males varied to greater extent in anthropometry with yearly height increases peaking at 8.7 and 10.5 cm in M1 and M2 respectively, compared to 0.7 and 3 cm across the whole three season period in F1 and F2. Peak growth rates measured in young males and females of European ancestry display magnitudes of 8.2 – 10.3 and 7.1 – 9.1 cm·year^{-1} respectively (Malina *et al.,* 2004) therefore it would be expected that the males in this study were closer to APHV than the females leading to a greater maturation effect. Within the longitudinal case study by Till and colleagues (2013b) growth rates of early and late maturing male elite rugby league players between under-13 and under-15 groups ranged from between 0.5 to 5.61 cm·year^{-1} displaying the variation observed in other sports across a range of maturation status. The variation in bodymass from this study is lower that Till *et al.* (2013b) who found a range of 5 to 23 kg·year^{-1}, elite male and female sailors ranged from approximately -0.6 to 6.4/3.5 to 7.2 and 4.2 to 7.3/-0.5 to 3.4 kg·year^{-1} respectively this is not surprising due to the benefits of increased mass to succeed in the contact nature of rugby league. Maximal values were in line or slightly lower than non-athletic data in North American and Europeans obtained by Malina *et al.* (2004) who found top end ranges to be 8.8 ± 2.4 and 10.3 ± 1.9 kg·year^{-1}.

In physical fitness tests within this study a different pattern to anthropometry emerged, with large variation in differences in the majority of tests in all four sailors, when combining test periods gives approximately 1-year blocks revealing the following maximum improvements: T-test: -1.39 sec and -1.01 sec in M1 and F1, SLJ: +38 cm and +33 cm in M1 and F1, press-ups +14 and +13 reps in M2 and F2, supine pulls: +14 and +12 in M1 and F1 and bleep test: +880m and 280m in M1 and F2. Large improvements in overall physical fitness were witnessed in both female and male sailors (44% in 1.1 years and 20% in 0.7 years respectively). Less variation in females is expected in general due to possessing smaller frames and heights, and a lower range of strength and motor performance abilities (Malina *et al.,* 2004) this data reveals the importance of the awareness of individual variation in physical fitness that occurs during adolescence. Compared to previous longitudinal research in elite male youth soccer players who were part of the Ghent Youth soccer project (GYSP) greater magnitudes of improvement were observed in the current study in SLJ and 20mSRT over yearly periods. Improvements around PHV of up to 10.5 cm·year^{-1} in SLJ, and 1.5 min·year^{-1} in 20mSRT, which equates to approximately 360m based on the number of shuttles per level (9 to 11). Players of different performance level in the GYSP were exposed to consistent volumes of training throughout the duration of the study (3-6 hours·week^{-1}), training volume was not recorded in the current study, possibly highlighting a reason of greater improvements from within season variation.

In the case of the male sailors who were CA-matched, M2, the later maturer did not 'catch-up' over the study, remaining approximately 20% lower in overall fitness. When comparing physical fitness scores relative to BA in earlier versus later maturers, in females the scores appeared similar at an equivalent 15.4 years at T (overall score was 63 and 69% respectively), the later maturer (F2) had enhanced her physical advantage by T+1 outscoring F1 by 13%. In male sailors at 15.2 years scores were 45 and 65% (M1 and M2 respectively), revealing a tendency towards the late-maturers performing better at equivalent BA, possibly due to more opportunity to train from being chronologically older, and from being more psychologically mature. The longitudinal development relative to BA-matched population and the difference between CA and BA benchmarks are displayed in Figure 8.2 and Figure 8.3. Regular large variation was observed against the age-matched population using both methods, with z-score differences of > ± 1 between time points in females and males. Some of these step-changes occurred across the population mean, potentially having consequences based around informing selection/deselection opinion.

A key aspect to acknowledge in youth athletic development is maturity timing, which can vary in tempo and magnitude (Malina *et al.,* 2004). In light of this variation, a standardised point typically reported is the APHV, denoting the CA at the maximum increase in height during the adolescent growth spurt, is used to assess maturity timing. PHV is impacted by changes in the adolescent body, primarily through hormonal development where growth is stimulated by androgens and estrogens that promote anabolism via nitrogen retention. Androgens (e.g. testosterone) drive bone growth through increased growth hormone which in turn stimulates insulin-like growth factors (IGF-I) (Malina *et al.,* 2004). It is contended that these hormonal and growth developments facilitate enhanced physical fitness performance around the APHV (Philippaerts *et al.,* 2006), or more specifically 0.8 to 1.2 years post-PHV in time with peak increases in bodyweight (PWV) likely from greater muscle mass (Malina *et al.,* 2004). In a non-athletic population mean estimated APHV occurs at 11.4 – 12.2 years in females and 13.8 – 14.2 years in males, athletes have been shown to vary from 12.0 to 13.2 years in females and 12.6 – 15.0 in males, with the extremes of younger ages coming from rowing and later from gymnastics (Malina *et al.,* 2004).

Maturity timing was estimated in this study through the use of Khamis and Roche (1995), which identified both female sailors and M1 (earlier maturer) were post-PHV, and M2 spanned pre-during and post-PHV during the study period. M2 missed profiling at T-3 and is therefore difficult to pinpoint accurate APHV as growth achieved 10 cm during T-4 to T-2 (1.2 years) which is comparable to magnitude of male PHV (Malina *et al.,* 2004) with a deceleration in following time points. In all sailors, peak improvements in physical fitness occurred in line with the greatest increases in bodymass, based on the timings of other anthropometric characteristics, in most cases probably relating to PWV: F1 increased 44%

during T-4 to T-2 (7.3 kg increase), F2 increased 22% during T-4 to T-3 (2.4 kg), M1 increased 13% during T-3 to T-2 (5.6 kg) and M2 increased 16% during T-4 to T-2 (7.2 kg) and 20% during T-1 to T (2.8 kg) potentially supporting the previous research of physical fitness relating to increases in muscle mass (Malina *et al.,* 2004; Philippaerts *et al.,* 2006). Though in a range of physical fitness tests further increases continued, possibly due to individual differences in muscle mass increases and volume of training (Philippaerts *et al.,* 2006). A limitation of this study was not measuring body composition e.g. skinfolds, as this would aid the confirmation of changes in lean body mass.

When comparing the differences across at each time point using BA versus CA (Figure 8.2 and Figure 8.3), this generally improved sailor standing relative to mean in later maturers, with the opposite evident in earlier maturers, which is in line with previous research that highlighted that athletes may be (dis)advantaged based on comparison with CA categories (Armstrong *et al.,* 1998; Till *et al.,* 2013a). Maturation has been shown to affect physical fitness in previous studies (Matthys *et al.,* 2013a; Till *et al.,* 2013a; Till *et al.,* 2013b; Vaeyens *et al.,* 2006) and in this study overall fitness change from T-4 to T+1 was closely linked to the increase in BA between sailors of the same gender regardless of maturation status – males both increased by 2.8 years and increased physical fitness by 39 and 41%, F1 increased by 1.7 years compared with 1.0 years in F2 resulting in an increase of 50% versus 33%. However, clear relationships are difficult to classify as it is contended that maturation status is more purely linked to anthropometry, in height especially, as there is less interaction with confounding factors such as training volume or nutritional intake (Beunen *et al.,* 1978). Although the pattern of differences between BA and CA were much clearer in male compared to female sailors, on reflection data displayed an inconsistent interaction of maturation and physical development during adolescence in both female and male sailors.

This inconsistency confirms the consensus of research in talent, where it is viewed that cross-sectional ‘snap-shots’ of ability and physical characteristics are extremely limited, as they don’t take into account the variation of developmental trajectories observed through adolescence (Till *et al.,* 2013a; Till *et al.,* 2013b; Vaeyens *et al.,* 2008). Instead, sporting pathways should focus on longitudinal monitoring, using physical profiling to aid the TDE process by providing a set of normative values that may be used to track sailors against longitudinally that can aid selection, inform training prescription and help monitor progression (Lidor *et al.*, 2009). Purely cross-sectional selection is a dangerous process, especially at younger ages, as physical characteristics that separate athletes at one time point may not stay through until late adolescence or adulthood (Abbott and Collins, 2002). It should be noted that even with added information of developmental trajectories and maturation status, the pathway to elite adult sporting success in complex and does not automatically translate to performance (Suppiah *et al.,* 2015; Till *et al.,* 2013a).

Cross-sectional and grouped longitudinal research designs do not reflect the detail necessary to understand the true variation within the maturation of individual athletes, vital to understand the TDE process. Although data of this type may be used as a benchmarking process, as long as it accounts for BA. This study used an individual case study design similar to Till *et al.* (2013b), the male sailors who were CA-matched provide a comparable population in terms of gender and starting age being within the original paper. The female sailors represent a novel group where CA was different, but in the last few data points were similar in BA due to the differences in maturation. The benefits of this study's design are similar to Till *et al.* (2013b) in that it allows for the long-term analysis of individual variation through a TDE environment that previous cross-sectional studies do not. Choosing a small sample of four sailors is a limitation, but a requirement to answer the key TDE research questions, the biased selection of sailors in this study could be viewed as a limitation, though as Till and colleagues (2013b) stated, selecting athletes based on a range of factors including class type, age and maturation status) aids understanding of potential variation across adolescence, plus if another four sailors were chosen different results would have been evident, further strengthening the methods employed in this study. This study does not intend to extrapolate findings to the population, but purely present the variation that is evident in a small sample of developing elite male and female sailors within the Olympic pathway.

As in the previous study, limitations exist in the estimation of maturity status and timing, especially around typical periods of accelerated growth (Beunen *et al.*, 1997; Khamis and Roche, 1975). The estimation of BA using the UK 1990 reference standards (Freeman *et al.,* 1990) may be viewed as a limitation, as the population is non-specific in terms of athletic or maturity status. It cannot be discounted that sailors experienced a degree of learning effect or between-session test-retest error, even though prior opportunity for practice or multiple trials were given. Finally, without full detail of training volume, it is difficult to attribute differences purely to changes in maturity status or timing, This study was novel in that no longitudinal research has been conducted in elite Sailing. Relative to case study designs, the ages of the participants exceed the range monitored in previous studies, plus this study adds knowledge to the dearth of research within elite youth sportswomen outside of gymnastics.

8.5 Practical applications

It is evident that large variation occurs within and between female and male sailors pre-, during-, and post-transition into elite Youth squads, further strengthening the argument for longitudinal assessment of athletes within a TDE framework, rather than early (de)selection based on one-off cross-sectional snap-shot assessments. Observing the variation of introducing maturation status in the tracking young elite athletes in this study, it is important to account for BA while applying cross-sectional benchmarking as part of a long-term assessment.

Chapter 9 General Conclusion

To address the increased competitiveness at elite senior level, where a higher number of countries are winning a larger share of Olympic and world championship medals (DeBosscher *et al.*, 2007; Rees *et al.*, 2016), it is accepted that maintaining a constant stream of athletes capable of elite success must be achieved (Vaeyens *et al.,* 2009). This is confirmed in the increased return of greater funding and resources placed into to the development of elite athletes (DeBosscher *et al.*, 2013b; Hogan and Norton, 2000). A pathway programme that has established the facets of elite performance and can identify athletes with the potential for successful progression can then focus resources to make the greatest impact (Abernathy, 2008) such as increased access to elite coaching, sports science support and funding (Vaeyens *et al.,* 2009).

The predictive accuracy of elite Junior and Youth progression into elite Senior participation and/or success is low, with a typical range of 6 to 35% across a variety of sports: Australian football (Robertson *et al.*, 2014), cycling (Schumacher *et al.*, 2006), rugby league (Till *et al.*, 2014), gymnastics (Pion *et al.*, 2016) and football (LeGall *et al.*, 2010; Ostojic *et al.*, 2014). When considering the poor predictive ability of elite sporting pathways especially at a young age, focus instead has been directed towards optimising the development of athletes identified as talented with the potential of future elite success, termed 'Talent Development' (Abbott *et al.*, 2002; Abbott and Collins, 2004; Martindale *et al.*, 2005; Vaeyens *et al.*, 2008).

Elite sailing is a complex sport that requires the combination of many factors including decision-making, cognitive function, tactics and a large technical component both in terms of boat design and physical skills (Bojsen-Möller *et al.*, 2007; Sjøgaard *et al.*, 2015). In recent Olympic cycles changes in the format of elite sailing has resulted in a more competitive and physically demanding sport (Bojsen-Möller *et al.*, 2014). Physical characteristics of elite sailing have been researched, with the predominance taking place in hiking positions, less is known in trapeeze and board sailors. A variety of anthropometrical sizes and physical abilities are witnessed in Olympic class sailing, mainly due to an attempt to maximise righting moment and boat speed while keeping body mass within specific boundaries for different classes (Bojsen-Möller *et al.*, 2014).

Elite Junior and Youth sailing has received little attention, with all studies focusing on hiking classes. Most studies have investigated physical indicators of performance using sailing-specific assessments (Callewaert *et al.*, 2014b; Tan *et al.*, 2006). Non-specific physical assessments have shown elite sailors exhibiting enhanced physical characteristics than non-elite sailors and other elite sporting youths in strength, endurance, aerobic fitness and co-ordination (Burnett *et al.*, 2012; Callewaert *et al.*, 2014a; Callewaert *et al.*, 2014b; Deforche *et al.*, 2003; Matthys *et al.*, 2013b; Tan *et al.*, 2006; Vaeyens *et al.*, 2006). Although when considering the low volume of sailing-specific training in these studies, greater physical competency may be due to participation in other sports (Callewaert *et al*., 2014b).

Physical characteristics are key to developing complex sports-specific skills (Abbott *et al.*, 2002; Gagné, 2004; Jess and Collins, 2003). Lloyd *et al.* (2015a) devised a physical model of development (Youth Physical Development model) where critical steps of the development of physical characteristics are displayed such as: balance, co-ordination, strength, agility, power and aerobic endurance (Bergeron et al., 2015). Proficiency in these areas have been shown to enhance sporting development through a number of areas: improving the effectiveness and quality of hours of practice and skill development (Elferink-Gemser *et al.*, 2010; Kliegl *et al.*, 1989; Rees *et al.,* 2016; Tucker and Collins, 2012), increasing the opportunity for practice through a decreased risk of acute and overuse injury (Lauersen *et al.*, 2014) and improvements in self-esteem and motivation (Lloyd *et al.*, 2015a).

Monitoring physical characteristics is seen to add objectivity to the subjective coach snap shot assessments of playing ability (Abbott *et al.*, 2002), with the aim of supporting a more directed plan of athlete development (Bompa and Haff, 2009). It is key however to acknowledge the varying trajectories of physical development in athletes especially during periods of accelerated growth (Bergeron *et al.*, 2015; Gulbin *et al.*, 2013; Lidor *et al.*, 2009) and that sporting development is multi-factorial and strengths in one area may be compensated for in other areas (Williams and Ericsson, 2005). The impact of physical characteristics to distinguish between performance level and stage of development varies across different sports (Elferink-Gemser *et al.*, 2004; Franks *et al.*, 1999; Lawton *et al.*, 2012; Lidor *et al.*, 2009; Matthys *et al.*, 2013b; Mohammed *et al.*, 2009; Pearson *et al.*, 2006; Till *et al.*, 2013a; Vaeyens *et al.*, 2006). Tracking athlete's physical characteristics longitudinally acknowledging maturation status relative to future elite success may enable talent programmes focus resources to maximise athlete potential based on the needs of their individual trajectory (Allen *et al.*, 2014; Lawton *et al.*, 2012; Vaeyens *et al.*, 2008) and formed the basis of this thesis.

9.1 Experimental chapters

- Chapter three was the first piece of research to identify key characteristics of successful elite development in sailing using semi-structured interviews with a sample of experienced elite pathway coaches across a range of sailing classes, plus corroboration with a high level elite sample of athletes who have all been ranked within the top two in the world including multiple Olympians. First order themes including components of fitness and anthropometry were analysed from just under 1,485 individual quotes within the raw data themes of: Components of fitness; Strength, Conditioning, Aerobic fitness, Agility, Balance, Co-ordination, Power, Flexibility, Whole body effort, Injury free and All-round fitness, Anthropometry; Within anthropometrical range and Leverage.

  Commonality was observed across the majority of physical characteristics, revealing a high level of agreement between elite pathway coaches and elite athletes when considering the key characteristics of successful elite sailor development. Differences in raw themes between participant groups were attributed to the role of elite coaches in encouraging an environment of hard work, a more detailed view of relatively recent information recall compared to the athletes, and a different experience of racing between Youth and senior level. It is also possible that athletes recollected previous youth experience through rose-tinted lenses (Mitchell and Thompson, 1994).

  A key aspect of successful development for elite sailors was around transitions, with a number of elite athletes and coaches referencing the significant steps when progressing through to elite senior participation in a range of components of fitness including: Strength, Conditioning, Aerobic fitness, All-round fitness and Power. The physical demands of developing elite sailors differ when transitioning up the pathway and between classes revealing a range of potential impact of physical development, therefore support should be tailored based on individual's current and potential future requirements.

- Chapter four investigated the reliability, validity and interrelationships of upper body strength assessments in order to establish the test to be used in the Olympic pathway physical testing battery. All assessments displayed high levels of reliability (ICC = 0.988 – 0.999) in line with previous research (0.96 – 0.99) found in 1RM bench press and bench pull exercises (Bell *et al.,* 1993; Invergo *et al*., 1991; Lawton *et al*., 2013; Levinger *et al.,* 2010; McGuigan *et al.,* 2010; McGuigan and Winchester, 2008). Field tests were shown to be valid when correlated to 1RM tests in a sample of recreationally trained men and women (r = 0.92 – 0.98). A plateau was observed within one to two familiarisation sessions in all strength assessments (P > 0.056).

In line with Baumgartner and colleagues (2002) study, where a Press-up technique was assessed for objectivity, reliability and validity, correlations of r = 0.80 – 0.87 were found when comparing bench press performance at a percentage of body weight, 1RM scores were calculated relative to body mass which resulted in stronger relationships. The correlation of Supine Pulls to 1RM were stronger than previously reported (Woods *et al.,* 1992). When considering the time-conscious environment of mass field testing within the Olympic pathway and the strong level of reliability of press-up and supine pull tests, these were chosen as the strength testing methods in the physical testing battery.

- Chapter six gained understanding of the variation in accuracy of non-invasive equations for predicting peak adult height (PAH) (Khamis and Roche, 1995; Sherar *et al.,* 2005) from measuring PAH in previous elite Junior and Youth sailors in the Olympic pathway since 2004. Based on the appropriateness of these methods, the Khamis and Roche (1995) method was selected to predict PAH and also to estimate maturation status in further studies. The findings of this chapter enable the Olympic pathway to advise preferable routes of development specific to most-suited Olympic classes and be more confident in the monitoring of sailor progression relative to maturation. This was in agreement with findings in Chapter three, where it is accepted that when reaching elite Senior level that being within the correct anthropometrical range is of key importance relative to the different classes and positions amongst the Olympic classes (Bojsen-Möller *et al.*, 2007; Bojsen-Möller *et al.*, 2014).

- Chapter seven aimed to further the studies of Bojsen-Möller *et al.* (2007) and Bojsen-Möller *et al.* (2014) who grouped and analysed the physical requirements of Olympic sailing into hikers, trapeeze and boardsailors. Using the physical profiling test battery created from empirical chapters within the thesis collected twice a year from elite pathway sailors from 2012, this chapter identified the anthropometric, maturation and physical characteristics of elite Junior and Youth sailors. The outcomes of this chapter address the gap of understanding below Olympic class sailing, and provides cross-sectional benchmarks for pathway sailors for the first time dependent on level and class type.

- Elite coaches and athletes were in consensus when acknowledging the increase in physical demands around key transition points moving between Junior to Youth and Youth to Olympic class sailing (Chapter three). Using the physical profiling test battery created through interactions of Chapter three and four collected twice per season from elite pathway sailors, Chapter eight identified the longitudinal development of physical characteristics in elite sailors around the Junior to Youth transition point accounting for the potential impact of maturation (Pearson *et al.,* 2006). Identifying the intra- and inter-individual variation of physical development around this key transition point will aid the programme to support developing sailors, and prescribe physical benchmarks relative to BA to aid preparation for the step up in level.

9.2 Practical Applications

The findings of this thesis include confirming a physical profiling process for the British Sailing Team's Olympic pathway using the key physical characteristics outlined within Chapter three. A number of these physical factors have been shown to differentiate between elite and non-elite sailing performance and relate to performance rankings which could serve as key indicators towards elite progression (Lidor *et al.,* 2009; Pearson *et al.,* 2006). As part of a physical profiling process in Chapter 5, Supine pulls and press-ups (Baumgartner *et al.,* 2002) were accepted as reliable and valid measures of strength to be used within the testing battery. Through the use of Khamis and Roche (1995) calculations for estimating %PAH and BA using the 1990 UK growth reference standards (Freeman *et al.,* 1990), this enabled the Olympic pathway to establish elite benchmarks to track sailors' physical development to direct resources and support effectively to support development created around individual needs (Allen *et al*., 2014).

There is a scarcity of research investigating the developmental process of Olympic sailors. This thesis has increased the understanding of physical development of elite sailors within the Olympic pathway, confirming key characteristics of successful elite development from elite coaches and sailors. A complete sailing-specific physical testing battery has been confirmed to enable robust assessment of a broad set of physical competencies required to meet the ever changing Olympic class environment. Using this battery of tests, a novel cross-sectional analysis of pathway sailing classes in males and females has been created, providing the first insight into physical requirements between classes below Olympic level. Due to the differences in maturity timing observed between female and male sailors at Junior level, it is recommended that greater awareness of gender differences are promoted to impact development at that stage.

The thesis concluded with the requirement that investigating the progression of physical characteristics around the Youth transition point must be made relative to the biological age of the population mean to account for the effects of maturity. The individual variation in physical development though the pathway has been presented, highlighting the need for longitudinal monitoring of sailors rather than decisions on physical competency based on one-off snap shots.

The thesis presented provides a progressive systematic plan to create a physical profiling battery for a sport pathway, and displays a method of tracking change of individual athletes relative to biological maturation and the population mean through use of z-scores.

9.3 Future research

Through continuing monitoring and recording of this physical data, the British Sailing Team will be able to gain greater understanding of the physical development of Olympic sailors. Further work to build on this thesis should include more time spent validating the biological age estimate using %PAH from the methodology of Khamis and Roche (1995). To be more confident of PAH prediction continue to record PAH in sailors who have been measured as part of the pathway, especially in males, to assess additional growth post-17.5 years of age and whether this growth is systematic of sailors or purely through outliers. Physical characteristics only were covered in this thesis, using the content analysis from Chapter three further areas of research could be investigated, for example psychological or developmental characteristics or the integration between physical and psychological processes.

To be of most use to sporting pathways research should ultimately be guided towards understanding the indicators of potential future success at Olympic and/or World Championship level. Whilst the intention is not the identification of talent (and selection/de-selection) using these indicators, over time a picture of a scaling of importance of these factors could distinguish between super-elites and the rest to enable a more focused individual level of support within the talent development environment.

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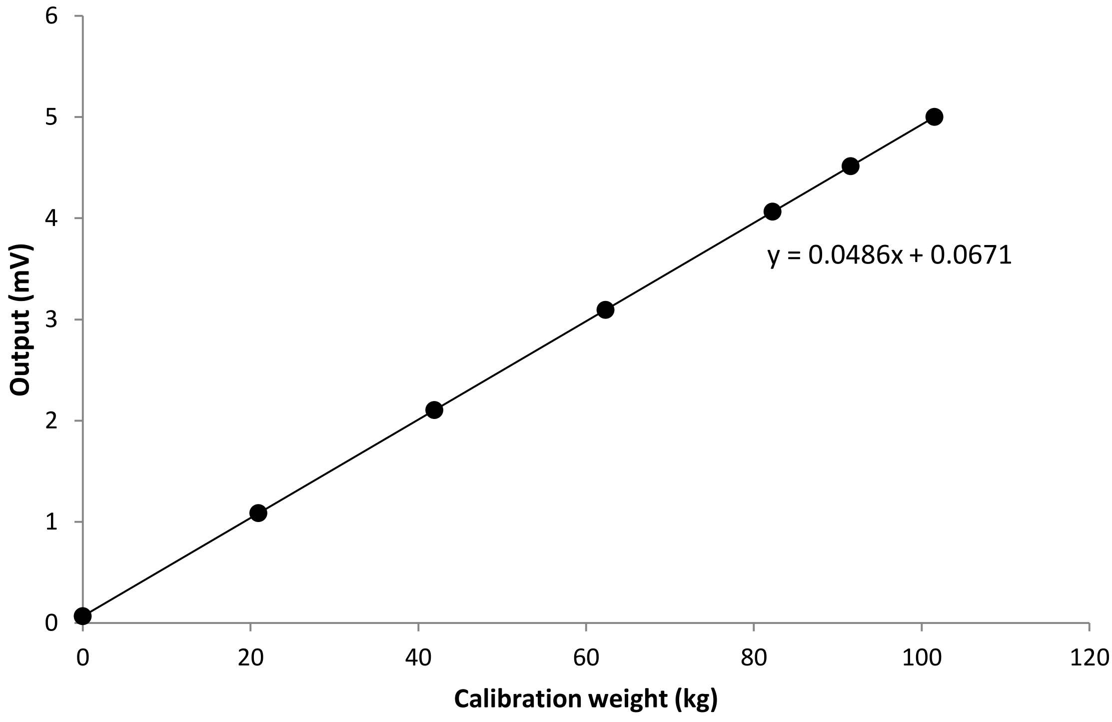
Chapter 11 Appendices

Appendix 1 – Olympic pathway sailing classes

Appendix 2 – Regression calculations for ISO testing in Chapter Fi

Plate combination	Weight Kg	Actual Weight Kg	Output mV
None	0	0.00	0.00
1	20	20.95	1.39
1 + 2	40	41.91	2.79
1 + 2 + 3	60	62.32	4.15
1 + 2 + 3 + 4	80	82.23	5.48
1 + 2 + 3 + 4 + 5	90	91.54	6.10
1 + 2 + 3 + 4 + 5 + 6	100	101.53	6.77
1 + 2 + 3 + 4 + 5	90	91.54	6.10
1 + 2 + 3 + 4 + 5	80	82.23	5.48
1 + 2 + 3	60	62.32	5.15
1 + 2	40	41.91	2.79
1	20	20.95	1.40
None	0	0.00	0.00

Weight plate no.	kg
1	20.951
2	20.962
3	20.409
4	19.904
5	9.316
6	9.985



Appendix 3 – Height added to current measurement to achieve predicted PAH (Sherar *et al.,* 2007)

	Growth (cm) left before adult stature						
	MALE			FEMALE			
Years from PHV	Early	Average	Late	Years from PHV	Early	Average	Late
-4.0	45.29	40.09	34.73	-4.0	42.61	38.81	34.35
-3.9	44.75	39.58	34.28	-3.9	42.05	38.24	33.81
-3.8	44.21	39.08	33.83	-3.8	41.49	37.67	33.27
-3.7	43.66	38.57	33.39	-3.7	40.94	37.11	32.74
-3.6	43.11	38.07	32.94	-3.6	40.39	36.55	32.20
-3.5	42.55	37.56	32.5	-3.5	39.84	35.99	31.67
-3.4	41.99	37.06	32.05	-3.4	39.30	35.44	31.14
-3.3	41.43	36.55	31.61	-3.3	38.76	34.89	30.62
-3.2	40.85	36.05	31.16	-3.2	38.21	34.34	30.09
-3.1	40.27	35.55	30.72	-3.1	37.67	33.8	29.57
-3.0	39.69	35.04	30.27	-3.0	37.13	33.25	29.04
-2.9	39.1	34.54	29.83	-2.9	36.59	32.71	28.52
-2.8	38.52	34.04	29.38	-2.8	36.04	32.16	27.99
-2.7	37.93	33.55	28.94	-2.7	35.5	31.6	27.46
-2.6	37.33	33.05	28.49	-2.6	34.94	31.04	26.93
-2.5	36.74	32.55	28.05	-2.5	34.38	30.48	26.4
-2.4	36.15	32.06	27.60	-2.4	33.82	29.91	25.87
-2.3	35.56	31.56	27.15	-2.3	33.25	29.34	25.33
-2.2	34.97	31.07	26.70	-2.2	32.68	28.76	24.79
-2.1	34.39	30.56	26.24	-2.1	32.11	28.17	24.25
-2.0	33.80	30.06	25.77	-2.0	31.53	27.58	23.71
-1.9	33.21	29.55	25.29	-1.9	30.97	26.99	23.17
-1.8	32.62	29.03	24.79	-1.8	30.44	26.39	22.63
-1.7	32.03	28.5	24.28	-1.7	29.9	25.8	22.09
-1.6	31.44	27.95	23.74	-1.6	29.36	25.21	21.55
-1.5	30.84	27.4	23.2	-1.5	28.81	24.62	21.01
-1.4	30.23	26.83	22.63	-1.4	28.24	24.03	20.47
-1.3	29.61	26.24	22.05	-1.3	27.67	23.44	19.92
-1.2	28.98	25.63	21.45	-1.2	27.09	22.85	19.37
-1.1	28.33	25.01	20.84	-1.1	26.49	22.26	18.82
-1.0	27.66	24.36	20.22	-1.0	25.87	21.66	18.25
-0.9	26.97	23.69	19.59	-0.9	25.22	21.06	17.67
-0.8	26.24	22.99	18.96	-0.8	24.54	20.44	17.07
-0.7	25.48	22.26	18.33	-0.7	23.84	19.81	16.45
-0.6	24.68	21.51	17.68	-0.6	23.09	19.16	15.81
-0.5	23.84	20.72	17.01	-0.5	22.31	18.5	15.14
-0.4	22.96	19.88	16.31	-0.4	21.50	17.80	14.44
-0.3	22.04	19.01	15.56	-0.3	20.65	17.08	13.71
-0.2	21.07	18.09	14.76	-0.2	19.77	16.33	12.94
-0.1	20.07	17.14	13.92	-0.1	18.86	15.55	12.15
0.0	19.04	16.16	13.05	0.0	17.94	14.75	11.36
0.1	18	15.18	12.18	0.1	17.01	13.94	10.57
0.2	16.96	14.21	11.32	0.2	16.09	13.13	9.81
0.3	15.93	13.26	10.5	0.3	15.18	12.33	9.09
0.4	14.92	12.35	9.71	0.4	14.30	11.56	8.42
0.5	13.95	11.47	8.98	0.5	13.45	10.82	7.79
0.6	13.01	10.65	8.27	0.6	12.64	10.11	7.20

0.7	12.11	9.86	7.6
0.8	11.26	9.12	6.94
0.9	10.45	8.43	6.31
1.0	9.70	7.78	5.70
1.1	8.99	7.16	5.1
1.2	8.33	6.59	4.54
1.3	7.7	6.05	4.01
1.4	7.11	5.54	3.51
1.5	6.56	5.06	3.06
1.6	6.04	4.62	2.64
1.7	5.56	4.2	2.26
1.8	5.10	3.80	1.92
1.9	4.67	3.43	1.62
2.0	4.26	3.09	1.35
2.1	3.88	2.77	1.12
2.2	3.52	2.48	0.91
2.3	3.18	2.21	0.73
2.4	2.86	1.96	0.58
2.5	2.57	1.73	0.44
2.6	2.29	1.52	0.32
2.7	2.03	1.33	0.22
2.8	1.78	1.16	0.13
2.9	1.55	1.01	0.06
3.0	1.34	0.87	0.00
3.1	1.14	0.75	0
3.2	0.96	0.63	0.00
3.3	0.79	1.53	0
3.4	0.64	0.43	0.00
3.5	0.5	0.35	0
3.6	0.37	0.27	0.00
3.7	0.26	0.19	0
3.8	0.16	0.12	0.00
3.9	0.07	0.06	0
4.0	0.00	0.00	0.00

0.7	11.86	9.43	6.64
0.8	11.11	8.77	6.12
0.9	10.38	8.13	5.61
1.0	9.69	7.52	5.13
1.1	9.02	6.93	4.67
1.2	8.39	6.37	4.24
1.3	7.78	5.83	3.84
1.4	7.20	5.33	3.46
1.5	6.65	4.85	3.11
1.6	6.14	4.42	2.80
1.7	5.65	4.01	2.51
1.8	5.19	3.64	2.25
1.9	4.76	3.3	2.02
2.0	4.36	2.99	1.82
2.1	3.99	2.71	1.63
2.2	3.63	2.45	1.46
2.3	3.3	2.21	1.32
2.4	2.99	1.99	1.18
2.5	2.7	1.79	1.06
2.6	2.42	1.60	0.94
2.7	2.16	1.43	0.84
2.8	1.92	1.26	0.74
2.9	1.69	1.11	0.65
3.0	1.47	0.96	0.57
3.1	1.26	0.82	0.49
3.2	1.07	0.69	0.41
3.3	0.89	0.57	0.35
3.4	0.72	0.46	0.28
3.5	0.57	0.36	0.22
3.6	0.43	0.26	0.17
3.7	0.3	0.18	0.12
3.8	0.19	0.11	0.08
3.9	0.09	0.05	0.04
4.0	0.00	0.00	0.00

Appendix 4 – Calculation tables for predicition of PAH (Khamis and Roche, 1995)

Male Data

age	Intercept	height	weight	md	Bayer M	Bayer SD
4	-26.0521	1.23812	-0.48849	0.50286		
4.5	-27.2262	1.15964	-0.41692	0.52887		
5	-27.9942	1.10674	-0.36274	0.53919		
5.5	-28.3354	1.0748	-0.32344	0.53691		
6	-28.2291	1.05923	-0.29649	0.52513		
6.5	-27.9963	1.05542	-0.27938	0.50692		
7	-27.9361	1.05877	-0.26959	0.48538		
7.5	-27.9943	1.06467	-0.26462	0.46361		
8	-28.1169	1.06853	-0.26194	0.44469		
8.5	-28.2499	1.06572	-0.25905	0.43171		
9	-28.3392	1.05166	-0.25341	0.42776	75.61	1.68
9.5	-28.297	1.02174	-0.24253	0.43593	77.21	1.66
10	-28.0365	0.97135	-0.22388	0.45932	78.4	1.76
10.5	-27.5047	0.89589	-0.19495	0.50101	79.82	1.77
11	-26.649	0.81239	-0.16267	0.54781	81.3	1.94
11.5	-25.4165	0.74134	-0.13533	0.58409	82.54	2
12	-23.7546	0.68325	-0.11242	0.60927	84	2.23
12.5	-21.858	0.63869	-0.09341	0.62279	85.43	2.49
13	-19.9726	0.60818	-0.07781	0.62407	87.32	3.02
13.5	-18.1225	0.59228	-0.06509	0.61253	88.22	3.57
14	-16.3319	0.59151	-0.05474	0.58762	91	3.96
14.5	-14.6249	0.60643	-0.04626	0.54875	92.6	3.85
15	-13.0256	0.63757	-0.03913	0.49536	94.6	3.74
15.5	-11.4535	0.68548	-0.03283	0.42687	96	3.31
16	-9.9801	0.75069	-0.02685	0.34271	97.09	2.71
16.5	-8.8577	0.83375	-0.02069	0.24231	97.95	2.12
17	-8.3388	0.9352	-0.01383	0.1251	98.79	1.43
17.5	-8.6756	1.05558	-0.00575	-0.0095	99.28	1.01

Female Data

age	Intercept	height	weight	md	Bayer M	Bayer SD
4	-20.6566	1.24768	-1.0883	0.44774		
4.5	-16.4505	1.22177	-1.03701	0.41381		
5	-13.045	1.19932	-0.98161	0.38467		
5.5	-10.5103	1.1788	-0.92307	0.36039		
6	-8.9164	1.15866	-0.86236	0.34105		
6.5	-7.9838	1.13737	-0.80043	0.32672		
7	-7.3062	1.11342	-0.73826	0.31748		
7.5	-6.7638	1.08525	-0.6768	0.3134		
8	-6.2372	1.05135	-0.61704	0.31457		
8.5	-5.6065	1.01018	-0.55993	0.32105		
9	-4.7523	0.9602	-0.50644	0.33291	81.19	2
9.5	-2.7008	0.89989	-0.45754	0.35025	83.03	2.13
10	0.8501	0.82771	-0.41419	0.37312	84.76	2.42
10.5	5.0131	0.74213	-0.37736	0.40161	86.85	2.71
11	8.9011	0.67173	-0.34357	0.42042	88.65	2.88
11.5	11.6268	0.6415	-0.30898	0.41686	90.81	3.06
12	12.3029	0.64452	-0.27405	0.3949	92.61	3.27
12.5	10.8679	0.67386	-0.23924	0.3585	94.72	2.61
13	8.164	0.7226	-0.20499	0.31163	95.96	2.15
13.5	4.6598	0.78383	-0.17175	0.25826	97.17	1.7
14	0.8236	0.85062	-0.13999	0.20235	98.27	1.24
14.5	-2.8759	0.91605	-0.11015	0.14787	98.74	0.93
15	-5.9704	0.97319	-0.08268	0.0988	99.31	0.68
15.5	-7.8823	1.01514	-0.05805	0.05909	99.54	0.48
16	-8.0743	1.03496	-0.03669	0.03272	99.62	0.35
16.5	-6.1381	1.02573	-0.01906	0.02364	99.75	0.34
17	-1.6657	0.98054	-0.00562	0.03584	99.95	0.25
17.5	5.7513	0.89246	0.00318	0.07327	99.91	0.25

Appendix 5 – 1990 UK Reference standards (Freeman *et al.,* 1990)

Male						Female					
Age (years)	**Height (cm)**	**%PAH**	**Age (years)**	**Height (cm)**	**%PAH**	**Age (years)**	**Height (cm)**	**%PAH**	**Age (years)**	**Height (cm)**	**%PAH**
10.0	138.4	77.9	14.1	163.0	91.8	10.0	138.4	84.6	14.1	159.9	97.7
10.1	138.8	78.2	14.2	163.6	92.1	10.1	138.9	84.9	14.2	160.2	97.9
10.2	139.3	78.4	14.3	164.2	92.5	10.2	139.4	85.2	14.3	160.4	98.0
10.3	139.7	78.7	14.3	164.8	92.8	10.3	139.9	85.5	14.3	160.7	98.2
10.3	140.1	78.9	14.4	165.3	93.1	10.3	140.3	85.7	14.4	160.9	98.3
10.4	140.5	79.2	14.5	165.9	93.4	10.4	140.8	86.0	14.5	161.1	98.4
10.5	141.0	79.4	14.6	166.4	93.7	10.5	141.3	86.3	14.6	161.3	98.6
10.6	141.4	79.6	14.7	167.0	94.0	10.6	141.8	86.6	14.7	161.5	98.7
10.7	141.8	79.9	14.8	167.5	94.3	10.7	142.2	86.9	14.8	161.7	98.8
10.8	142.2	80.1	14.8	168.0	94.6	10.8	142.7	87.2	14.8	161.9	98.9
10.8	142.6	80.3	14.9	168.5	94.9	10.8	143.2	87.5	14.9	162.0	99.0
10.9	143.0	80.5	15.0	168.9	95.2	10.9	143.7	87.8	15.0	162.2	99.1
11.0	143.4	80.7	15.1	169.4	95.4	11.0	144.1	88.1	15.1	162.3	99.2
11.1	143.8	81.0	15.2	169.8	95.7	11.1	144.6	88.3	15.2	162.4	99.2
11.2	144.2	81.2	15.3	170.3	95.9	11.2	145.1	88.6	15.3	162.6	99.3
11.3	144.6	81.4	15.3	170.7	96.1	11.3	145.5	88.9	15.3	162.7	99.4
11.3	145.0	81.6	15.4	171.1	96.3	11.3	146.0	89.2	15.4	162.8	99.4
11.4	145.3	81.9	15.5	171.4	96.6	11.4	146.5	89.5	15.5	162.9	99.5
11.5	145.8	82.1	15.6	171.8	96.8	11.5	146.9	89.8	15.6	162.9	99.5
11.6	146.2	82.3	15.7	172.1	97.0	11.6	147.4	90.1	15.7	163.0	99.6
11.7	146.6	82.6	15.8	172.5	97.1	11.7	147.9	90.3	15.8	163.1	99.6
11.8	147.0	82.8	15.8	172.8	97.3	11.8	148.3	90.6	15.8	163.1	99.7
11.8	147.5	83.1	15.9	173.1	97.5	11.8	148.8	90.9	15.9	163.2	99.7
11.9	147.9	83.3	16.0	173.4	97.7	11.9	149.3	91.2	16.0	163.2	99.7
12.0	148.4	83.6	16.1	173.7	97.8	12.0	149.8	91.5	16.1	163.3	99.8
12.1	148.8	83.8	16.2	173.9	98.0	12.1	150.2	91.8	16.2	163.3	99.8
12.2	149.3	84.1	16.3	174.2	98.1	12.2	150.7	92.1	16.3	163.3	99.8
12.3	149.8	84.4	16.3	174.4	98.2	12.3	151.2	92.4	16.3	163.4	99.8
12.3	150.3	84.7	16.4	174.6	98.4	12.3	151.7	92.7	16.4	163.4	99.8
12.4	150.8	85.0	16.5	174.9	98.5	12.4	152.1	92.9	16.5	163.4	99.8
12.5	151.4	85.2	16.6	175.1	98.6	12.5	152.6	93.2	16.6	163.5	99.9
12.6	151.9	85.5	16.7	175.3	98.7	12.6	153.1	93.5	16.7	163.5	99.9
12.7	152.4	85.9	16.8	175.4	98.8	12.7	153.5	93.8	16.8	163.5	99.9
12.8	153.0	86.2	16.8	175.6	98.9	12.8	154.0	94.1	16.8	163.5	99.9
12.8	153.6	86.5	16.9	175.8	99.0	12.8	154.4	94.3	16.9	163.5	99.9
12.9	154.2	86.8	17.0	175.9	99.1	12.9	154.9	94.6	17.0	163.5	99.9
13.0	154.8	87.2	17.1	176.1	99.2	13.0	155.3	94.9	17.1	163.5	99.9
13.1	155.4	87.5	17.2	176.2	99.2	13.1	155.7	95.1	17.2	163.5	99.9
13.2	156.0	87.9	17.3	176.3	99.3	13.2	156.1	95.4	17.3	163.5	99.9
13.3	156.6	88.2	17.3	176.5	99.4	13.3	156.5	95.6	17.3	163.5	99.9
13.3	157.3	88.6	17.4	176.6	99.4	13.3	156.9	95.9	17.4	163.5	99.9
13.4	157.9	88.9	17.5	176.7	99.5	13.4	157.3	96.1	17.5	163.5	99.9
13.5	158.6	89.3	17.6	176.8	99.6	13.5	157.7	96.3	17.6	163.5	99.9
13.6	159.2	89.7	17.7	176.9	99.6	13.6	158.0	96.5	17.7	163.5	99.9
13.7	159.8	90.0	17.8	176.9	99.6	13.7	158.4	96.7	17.8	163.6	99.9
13.8	160.5	90.4	17.8	177.0	99.7	13.8	158.7	97.0	17.8	163.6	99.9
13.8	161.1	90.7	17.9	177.0	99.7	13.8	159.0	97.2	17.9	163.6	99.9
13.9	161.7	91.1	18.0	177.1	99.7	13.9	159.3	97.3	18.0	163.6	99.9

Appendix 6 – Participant information sheet (Chapter 5)

PLEASE READ THE FOLLOWING CAREFULLY

Study title: ***The development of a testing battery for an Olympic sailing pathway***

This information sheet provides details of one of the studies within my research project for completion of a PhD. The aim of this document is to outline the process of this study and give you all the information you need to decide on whether you will consider taking part.
This study will investigate a range of methods to record aspects of upper body strength, and the interrelationships between them. Both the validity and reliability of these methods will be analysed in regards to how appropriate they are to sailing. The main aim of this study is to help develop the testing battery that we deliver in our Olympic pathway fitness testing sessions. Should you agree to be involved in this research you would be required to commit to 4 gym visits: 2 x familiarisation session (90 min) and 2 x testing sessions (approximately 2hours) over the period of 2 weeks in which you will be performing 8 strength tests listed as follows:

1. 1-Reptition Max (RM) Bench press and Bench pull
2. 3 x Maximal isometric push and pull efforts
3. Maximum number of press-ups and modified pull-ups in one attempt
4. 3 seated maximal efforts on a Concept II dynamometer in the horizontal push and pull direction.

All the tests will be completed in each visit in the same order, with adequate rest given between each test so that fatigue does not impact on performance. It is important that you do not perform exhaustive exercise or drink alcohol in the 24 hours before the testing sessions, and that you try to maintain your diet and sleep patterns. Full technical advice, motivation and spotting (where appropriate) will be given in all tests so that they can be performed safely and effectively. You should eat a meal no less than 2 hours before testing to limit the effect of pre-nutrition on the results, and no caffeine the morning of the testing. Please arrive in a hydrated state i.e. light urine colour, and bring water with you.

Maximal strength testing does carry a risk of injury, though a standardised warm-up will be performed prior to high effort lifts to reduce the risk. If you have any injuries that you feel may affect your ability to exert maximal force please contact me on the email at the bottom of this sheet before taking part.

Individual results from the strength tests will be reported under pseudonyms to protect your confidentiality and personal data will be stored under these pseudonyms on a lockable laptop that only my supervisors (Dr. David Macutkiewicz and Dr. Mike Lauder and I will have access to. You are free to withdraw at any point during the study without giving any reason, the data collected may be removed from analysis if you so wish.

If you have any questions or concerns over your involvement with this research study at any point, please contact me on: *07760 161975* or *tim.jones@rya.org.uk*

This project has been approved in accordance with the University of Chichester Ethical Policy Framework
Thank you for your time

PHYSICAL PROFILING

The tests we are tracking progression are in the following components of fitness:

AGILITY

LEG STRENGTH / POWER

ANTHROPOMETRY

UPPER BODY STRENGTH/ENDURANCE & STRENGTH BALANCE

TRUNK ENDURANCE/CURRENT BACK HEALTH

AEROBIC CAPACITY

For a link to a video of all tests copy the following into your browser:
http://youtu.be/Mk7jdZ62KkQ

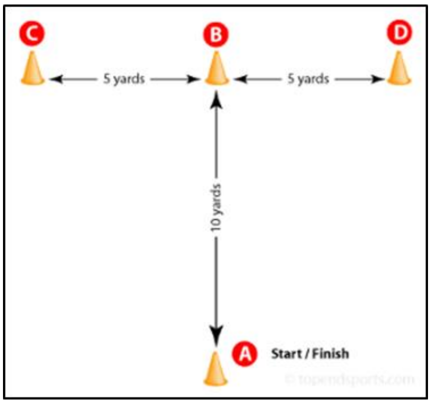
STATION 1

TEST: **T-TEST**
MEASURES: **AGILITY**

AGILITY: T-TEST

Aim of test: To complete the course as fast as possible with good technique while touching the cones at each change of direction
Score: Time (sec) – 2 attempts with fastest run counted
Description of test:

1. Start at cone A, sprint forwards to cone B
2. Sidestep LEFT to cone C
3. Sidestep RIGHT to cone D
4. Sidestep LEFT to cone B
5. Backpedal to cone A (start line)



Tips: **Feet do not cross over during sidesteps**
Stay low and balanced
Finish through the line at full speed
MUST TOUCH THE CONES FOR TIME TO COUNT!

STATION 2

TESTS: **STANDING LONG JUMP / HEIGHT, SEATED HEIGHT, ARMPSAN, BODY MASS**

MEASURES: **LOWER BODY STRENGTH & POWER / ANTHROPOMETRY**

LEG STRENGTH/POWER: STANDING LONG JUMP (SLJ)

Aim of test: Jump as far as you can in a horizontal distance taking off and landing on two feet.
Score: Distance (m) – 3 attempts with best score counted
Description of test:

1. Start from a standing position with feet lined up
2. Jump as far as you can outwards swinging your arms outwards to help develop power
3. Land balanced in a low squat position with both feet keeping knees 'soft' and bent, making sure you don't fall forwards or backwards otherwise the jump will not count.

Tips: Jump out and up for maximum distance
Use your arms to swing powerfully forwards
Pre bend your knees before jumping out like a coiled spring

ANTHROPOMETRY

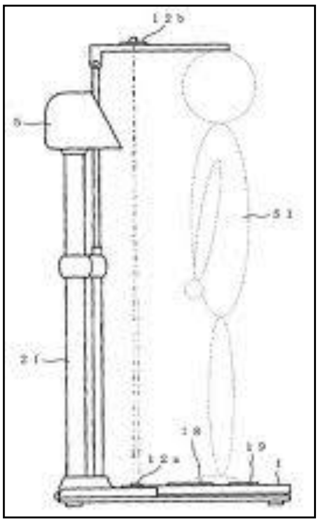
What it does: measures **GROWTH,** and tracks **MATURATION**
Aim of test: To identify the rate and amount of growth through your developing period
Score: Various (Height/Seated height/armspan, cm, Body mass, Kg)
Description of tests:

BODY MASS (Kg)

- Keep weight evenly spread
- Look forwards
- Stand still

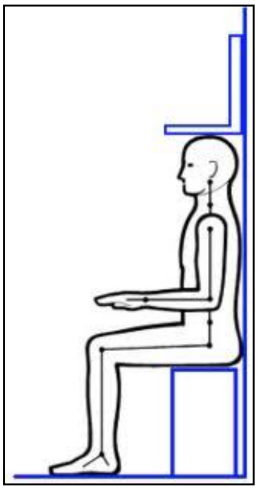
STANDING HEIGHT (cm)

- No tip-toes
- Take big breath in
- Head straight
- Eyes level
- Weight even
- Look forward



SEATED HEIGHT (cm)

- Sit tall
- Follow other directions from standing height



ARM SPAN (cm)

- Stand facing away from testers
- Keep back straight
- Keep arms level with ears
- Hold still

STATION 3

TESTS: **MAXIMUM PRESS-UPS & SUPINE PULLS**

MEASURES: **UPPER BODY STRENGTH AND ENDURANCE & STRENGTH BALANCE**

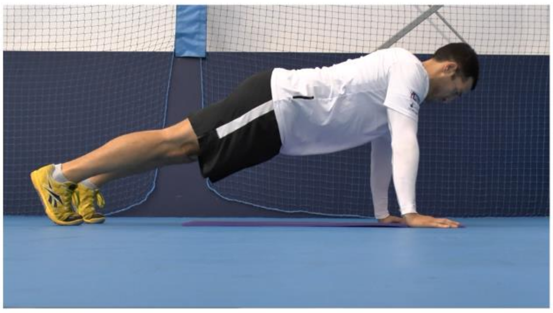
UPPER BODY STRENGTH: PRESS-UPS & SUPINE PULLS

Aim of test: Complete maximum number of repetitions of bodyweight exercises with correct technique to metronome timing of 2sec per repetition (1sec 'up' – 1sec 'down')
Score: Number of repetitions with good technique

Description of test (Press-up):

1. Start lying face down on the mat with feet hip width apart, hands placed flat on the floor **JUST OUTSIDE OF SHOULDERS,** elbows pointing towards the ceiling
2. Brace the hips and trunk while slightly lifting the knees from the floor so you are fully extended in the start position on the floor
3. 1 press-up = body pressed up under control to full extension of the elbows while body kept straight, then controlled down so that elbows are above back. ELBOWS MUST NOT POINT OUT DIRECTLY SIDEWAYS.
4. Reps will not count if you cannot perform with appropriate technique e.g. hips sagging, hips piking, pushing up in two movements, elbows not fully extended or going low enough during reps
5. If you cannot complete any more reps with good technique the test will be terminated.

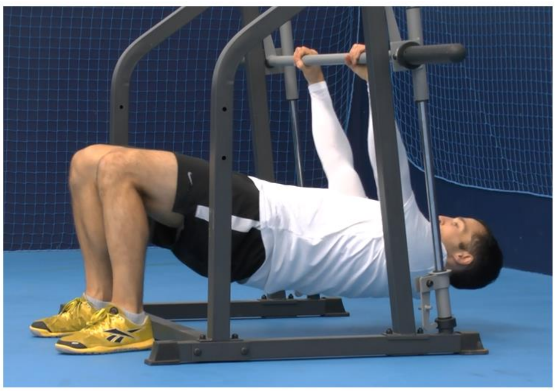
Tips: **Keep body braced with shoulders back**
Breathe in at the top and exhale forcefully on way back up

Description of test (Supine Pull):

1. Start lying face up on the mat underneath bar, arms are fully extended touching the bar with palms facing towards feet with shoulders lifted off the mat but the back is still in contact
2. Grip the bar just outside of shoulder width, feet flat on the floor with legs slightly bent, bring hips up into straight position.
3. 1 supine pull = body pulled up **SO THAT MID-CHEST TOUCHES THE BAR** while maintaining a straight body, then elbows are extended as body is lowered under control back to start
4. Reps will not count if you cannot perform with appropriate technique e.g. hips sagging, hips piking, elbows not fully extended or reaching 90°, pulling the bar too high/low

Tips: **Pull forcefully from start position to make sure chest touches bar**
Keep body braced and shoulders back




LAST TEST

TEST: **BLEEP TEST**

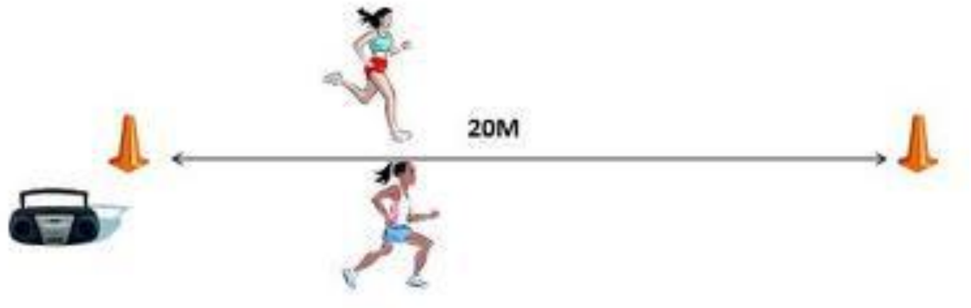
MEASURE: **AEROBIC FITNESS**

AEROBIC CAPACITY: BLEEP TEST

Aim of test: Keep running 20 m shuttles as long as you can or until a tester tells you to "STOP"
Score: Level
Description of test:

1. Run between lines that are 20 m apart to the sound of the bleeps
2. As the test progresses the bleeps get quicker, so you must run faster to keep up
3. If you do not make the line you will be warned
4. If you get two warnings you will be disqualified by the tester
5. The way the test should end is by reaching exhaustion (when you can't physically keep up with the bleeps anymore) **NOT** because you have just had enough!!

Tips: **Conserve energy for as long as you can**
It will be tough, but push yourself to the limits
Aim to be the last sailor standing at the end



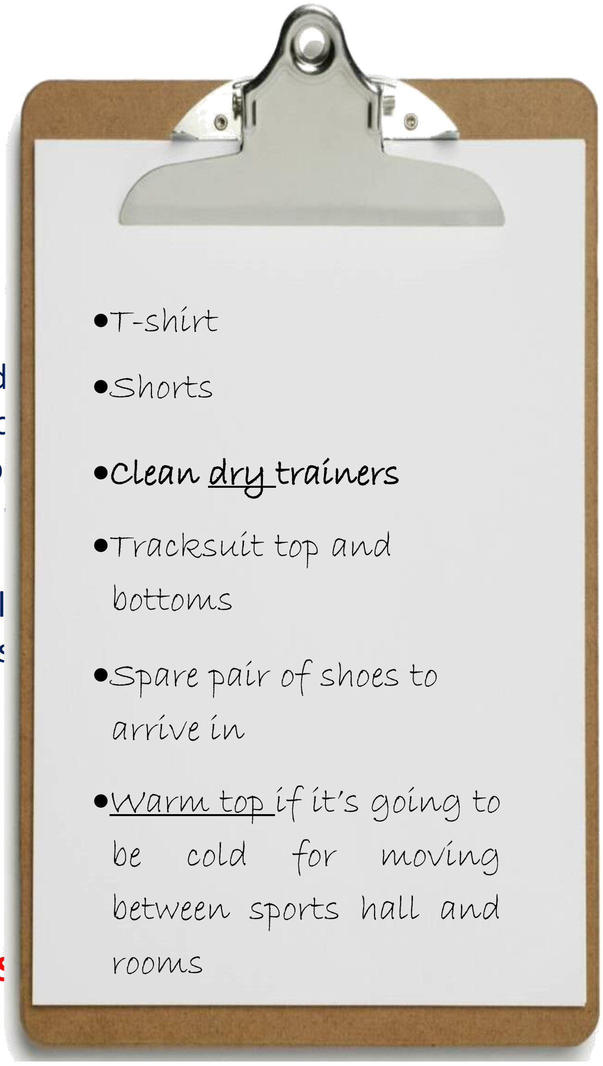
Checklist

To perform at your, it is imperative that you prepare – and that doesn't stop at having a good breakfast! (though that definitely helps). Optimal preparation will be achieved in partnership with who is helping you at home, and includes:

- **WHAT TO WEAR**
- **WHAT TO EAT/DRINK**
- **OTHER INFORMATION**

WHAT TO WEAR

As the testing will take place ind grippy **DRY** shoes are most impo (normal trainers will be fine), so bring these in a bag and put the inside before testing – as if it is raining, wet shoes wil the floor slippery and dangerous



WHAT NOT TO WEAR:

- **DIRTY, WET TRAINERS**
- **SKATE SHOES**
- **BAGGY JUMPERS/TROUSERS**
- **JEANS**
- **FLIP-FLOPS**
- **JEWELLERY**

IF YOU TURN UP IN ANYTHING THAT IS CONSIDERED INAPPROPRIATE YOU MAY BE EXCLUDED FROM THE SESSIONS

WHAT TO EAT/DRINK

PRE-TESTING

- Carbohydrate is main fuel that you need
  Have balanced meal around 2-3 hours before testing starts to allow time to digest

Good options include:

Cereal + milk
Baked beans/egg + toast
Porridge with banana

- If you are going to have a snack ~1 hour before testing to top up your energy stores, make sure it is a small one as you would have only just eaten e.g. half a cereal bar

Good options include:

- Fruit, cereal bars

- Make sure that you are hydrated in the morning

Have a glass of water at breakfast
Sip on water throughout the morning making sure you have around 300-500ml of fluids before the testing session
Pre-testing urine should be a light straw colour to indicate being well hydrated