FACULTY OF MEDICINE AND HEALTH SCIENCES
Department of Movement and Sports Sciences

MECHANISMS OF SUBMAXIMAL (QUASI-)ISOMETRIC KNEE EXTENSION EXERCISE RELATED TO DINGHY SAILING PERFORMANCE

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Dankwoord:

I make progress by having people around me who are smarter than I am and listening to them. And I assume that everyone is smarter about something than I am.   (Henry J. Kaiser)

I would like to thank the members of the examination board. Prof. De Bourdeaudhuij, Prof. Calders, Prof. Derave, Prof. Lenoir en Prof. Meeuwsen, bedankt voor het grondig nalezen van mijn thesis. Jullie specifieke expertise en waardevolle suggesties hebben mij aangemoedigd om vanuit het onderzoek meer praktische conclusies te formuleren en zodoende dit werk te verbeteren. Also a special thanks to our foreign member of the examination board, Prof. Gisela Sjøgaard. Not only for your good suggestions and attending my Phd-defense, but also for the organization of the sailing-symposium on the EJSS-congress in Barcelona last year and the opportunity to be part of the consequential special EJSS-issue (“Sailing & Science”). It is nice for our small research group that in that way our (limited) contribution to sailing research is recognized by the world-leading experts in the field. And personally, this gave me the motivation to start writing my Phd.

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Bert, ofwel ‘den Bertn’, ‘den Bèr’ of ‘Silly Bird’ genoemd, ik kon me geen betere collega voorstellen. Vele uren hebben we samen hard gewerkt en heb ik veel wetenschappelijke zaken van je geleerd, maar altijd in ‘ontspannen’ (soms misschien te ontspannen) sfeer. Het begon voor ons beiden in de containers, waar we met Fabian en Veerle altijd ‘rustig’ aan het werk waren. De “ettelijke opruimmomenten” (nadat Jan ons bureau eens bezocht had en hem letterlijk een vuilbakcontainer genoemd had), “de telefoontjes naar Rudi” en “de gezellige bezoeken van Johan Pion” behoorden daar tot de momenten van ontspanning. Ook onze Amerikaanse roadtrip (en ook een beetje het congres in Denver), het congres in Barcelona en Oostende waren echt topmomenten in mijn leven. Ik vergeet nooit “hoe bang ik was van beren (die uiteindelijk hertjes bleken te zijn) in de Rocky Mountains”, “de lama’tjes die ik uiteindelijk nooit zag”, “de zwartgestoofde pot en handdoek van ons ma”, “de rijkunsten van Inge met alle gevolgen van dien”, “de cointreautjes in de Rockie Mountains”, “Bert die doodgewoon met zijn petzel op zijn hoofd het Luxor hotel in Las Vegas binnenwandelt”, “de manier waarop Bert wijn proeft (of het ons toch zo wijsmaakte)” en “de jaeger bombs waar je altijd zo over sprak maar die we nog nooit gedronken hebben”. Bovendien vergeet ik ook zeker niet onze gesprekken in America (bij enkele glazen cointreau), Barcelona (bij meerdere kannen sangria) en Oostende (bij meerdere pintjes en een vettig pak frieten) die steeds zo verrijkend waren. Voor jou begint de eindmarathon nog maar, maar met je stalen conditie en goede coaches kan je deze zeker aan. Voor de mental coaching heb je ondertussen een nieuwe collega, Jasmien (aka "Jazzy"), die je zeker ook zal opvangen. En mocht je me toch nog missen, ge weet mij wonen e. Ik zal nooit kunnen terugdoen wat jij voor mij gedaan hebt.

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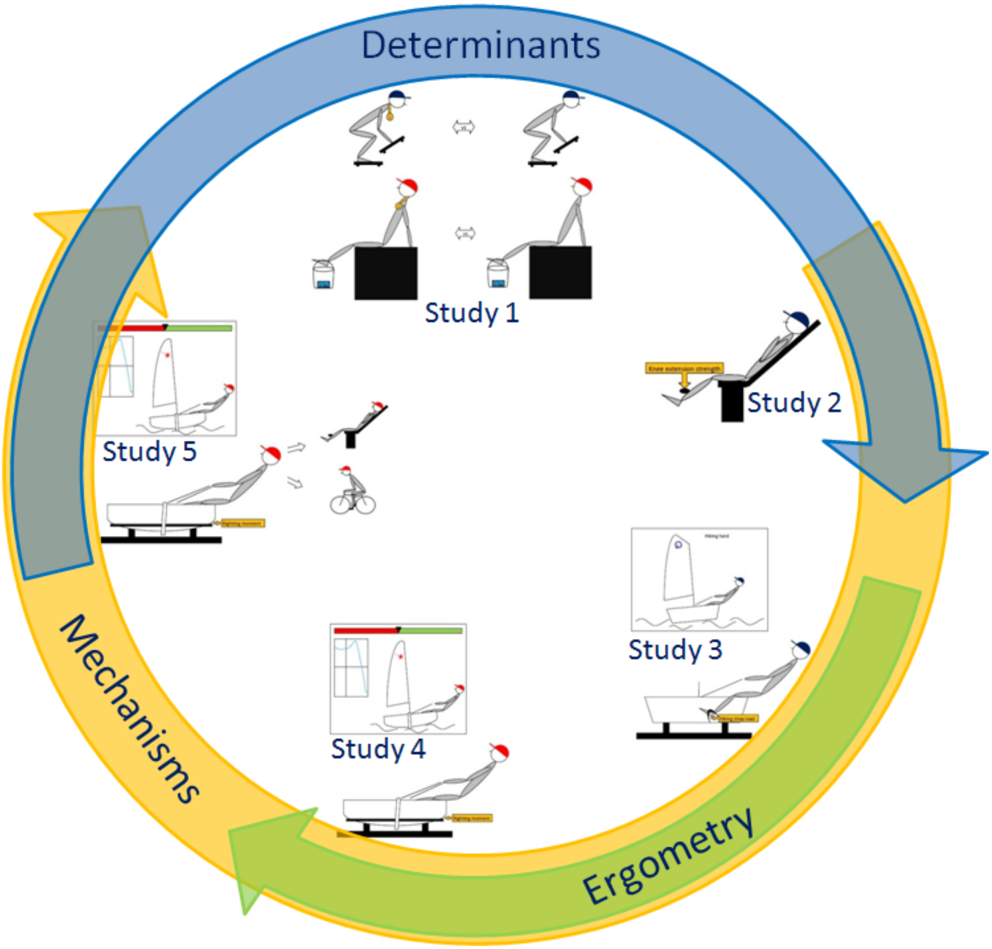
SUMMARY:


Determinants
Study 1
Study 2
Study 3
Study 4
Study 5
Mechanisms
Ergometry

Background

Dinghy sailing performance is related to hiking endurance (Blackburn & Hubinger, 1995; Tan et al., 2006; Vangelakoudi et al., 2007). However, there is no clear understanding of the underlying physiological mechanisms of hiking. Previous studies established during upwind sailing a significant disproportionate increase in heart rate (up to 75 % HR_{peak}) and oxygen uptake (up to 40 % VO_2peak), reflecting the isometric tension on the anterior body muscles (Vogiatzis et al., 1995). Furthermore, significant increases in both systolic and diastolic blood pressure indicate the isometric nature of this exercise (Blackburn, 1994). However, lactate concentration ([La]) during upwind sailing does not exceed 4 $mmol \cdot l^{-1}$ which suggests only a small oxygen and energy deficit during upwind sailing (Vogiatzis et al., 2008). Consensus was reached to use the term *quasi-isometric* to categorise the hiking exercise (Spurway, 2007). In the mean time, the cardiorespiratory, -vascular and metabolic demands during upwind sailing have been thoroughly investigated whereas the muscular mechanisms have only been superficially studied.

This research enhances our understanding of dinghy sailing performance by pursuing 3 research aims, that is: (1) investigating the determinants of dinghy sailing performance, (2) developing a sailing ergometer which accurately represents the physiological responses during on-water upwind sailing, and (3) exploring the physiological mechanisms during submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing exercise) with a distinct focus on the muscle level.

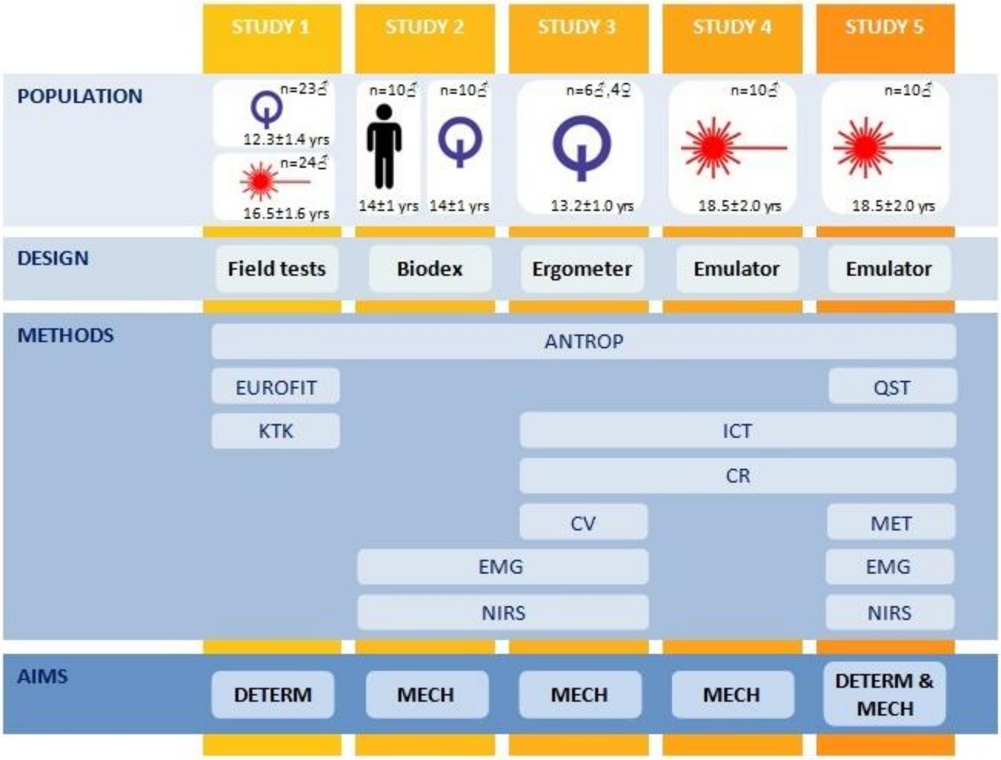


Figure A: *Overview of the population, study design, methods and aims of the 5 studies conducted in the original research. (Ϙ= Optimist sailors, ✶- = Laser sailors, Black sign = sedentary children, ANTROP = anthropometry, KTK = KörperKoordinationstest für Kinder, QST = quadriceps strength test, ICT = incremental cycling test, CR = cardiorespiratory measurements, CV = cardiovascular measurements, MET = metabolic measurements, EMG = electromyography, NIRS = near infrared spectroscopy, DETERM = determinants, MECH = mechanisms)*

To achieve these goals, five studies with each their own purpose and design have been conducted. The illustration (A) above demonstrates the different study populations, designs, methods and aims.

Results and conclusions

The determinants of dinghy sailing performance include motor coordination skills and incremental knee extension strength. Motor coordination skills for Optimist sailors (i.e. ≤ 15 years) were highly related to sailing level, whereas incremental knee extension strength endurance (i.e. measured by bucket test) for dynamic hikers (i.e. > 15 years) was related to sailing level. The contribution of incremental knee extension strength endurance to performance for Optimist and Laser sailors was related to a delay in muscle fatigue. The muscle fatigue for Laser sailors was clearly related to maximal quadriceps strength. This result emphasizes the importance of implementing dry-land motor coordination skill training for Optimist sailors and dry-land maximal strength training for Laser sailors.

In addition, an innovative biologically validated upwind sailing emulation ergometer was developed by applying a biofeedback system to measure the hiking moment. As such, the researcher can impose a certain quasi-isometric upwind sailing protocol to several subjects or to one subject on different occasions. The emulation ergometer can be implemented as tool for sailing performance diagnostics and training follow-up.

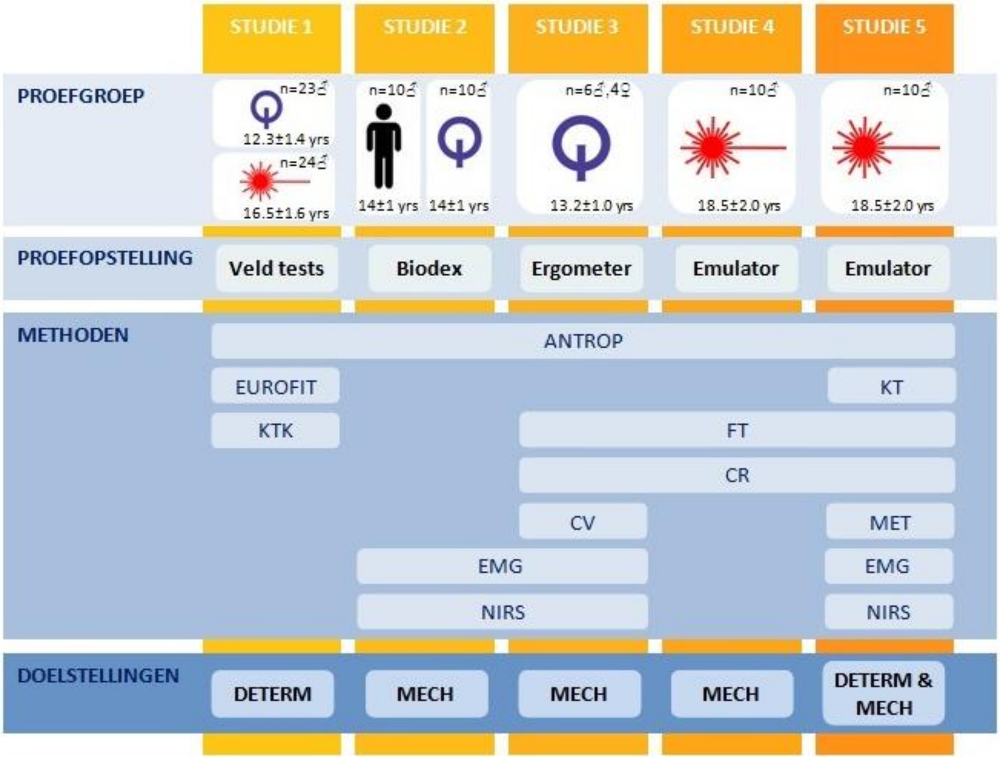
Optimist and Laser sailors' quadriceps muscle fatigue (as indicated by a decrease in mean power frequency an increase in root mean square) increased throughout submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing exercise). However, after an initial increase, a steady state phase was observed, presumably due to compensation strategies (e.g. tacking, fore and aft movements, and alternate-legs-strategy) conducted by the sailors to delay exhaustion. This results in a momentary relaxation of the quadriceps muscle causing a rapid outflow of deoxygenated blood and inflow of fresh oxygenated blood. Optimist sailors possess other fiber recruitment or O_2 extraction patterns, probably to postpone exhaustion and increase knee extension strength endurance, than untrained controls.

SAMENVATTING:

Achtergrond

Prestatie tijdens het zeilen in een zwaardboot is in sterke mate afhankelijk van hoe lang men de belastende uithangbeweging kan volhouden (Blackburn & Hubinger, 1995; Tan et al., 2006; Vangelakoudi et al., 2007). Echter, het is nog steeds onduidelijk welke de onderliggende fysiologische mechanismen zijn van dit fenomeen. In het verleden werd reeds aangetoond dat de hartfrequentie (HF) en de zuurstof opname (VO_2) tijdens het uithangen een disproportionele stijging (tot 75 % HFpiek en 40 % VO_2piek resp.) vertonen, wat impliceert dat de anterieure spieren een isometrische belasting ondergaan (Vogiatzis et al., 1995). Ook de stijging in zowel systolische als diastolische bloeddruk wijst op een isometrische oorsprong van de uithang-belasting (Blackburn, 1994). Alhoewel, het feit dat de lactaat concentratie tijdens het uithangen nagenoeg 4 $mmol \cdot l^{-1}$ bereikt, suggereert een minimaal zuurstof of energie tekort (Vogiatzis et al., 2008). In 2007 kwamen verschillende onderzoekers binnen dit onderzoekstopic tot concensus om de uithangbeweging te identificeren als een *quasi-isometrische* belasting (Spurway, 2007). Op dit ogenblik zijn de cardiorespiratoire, cardiovasculaire en metabole aanpassingen ten gevolge van uithangen reeds diepgaand onderzocht, terwijl de musculaire mechanismen enkel oppervlakkig onderzocht werden.

Dit onderzoek draagt bij tot een beter begrip van de prestatie tijdens het zeilen in een zwaardboot door 3 onderzoeksdoelen voorop te stellen: (1) het onderzoeken van de determinanten van zeilprestatie in een zwaard-boot, (2) het ontwikkelen van een zeilergometer die nauwkeurig de fysiologische acute aanpassingen tijdens het uithangen uitlokt, en (3) het beschrijven van de fysiologische mechanismen tijdens submaximale (quasi-) isometrische knie extensie bewegingen (als een deel van de uithangbeweging) met focus op spierniveau.



Figuur B: *Overzicht van de van proefgroep, proefopstelling, gebruikte methodes en doelstellingen van de 5 studies uitgevoerd binnen dit onderzoek. (Ϙ = Optimist zeilers, ✶- = Laser zeilers, zwart teken = sedentaire kinderen, ANTROP = antropometrie, KTK = Körper-Koordinationstest für Kinder, KT = quadriceps kracht test, FT =maximale fiets test, CR = cardiorespiratoire metingen, CV = cardiovasculaire metingen, MET = metabole metingen, EMG = electromyografie, NIRS = near infrared spectroscopie, , DETERM = determinanten, MECH = mechanismen)*

Om deze doelstellingen te bereiken werden 5 studies met elk een eigen onderzoeksopzet uitgevoerd. De figuur (B) hierboven geeft een overzicht van de verschillende proefgroepen, -opstellingen, methodes en doelen binnen elke studie opgenomen in dit onderzoek.

Resultaten en conclusies

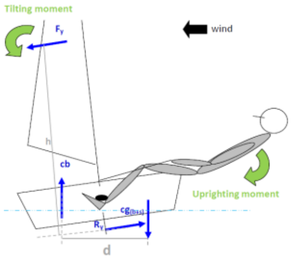
Met betrekking tot de determinanten van zeilprestatie in een zwaardboot bleek motorische coördinatie (naast knie extensie kracht uithouding) bij Optimist zeilers (i.e. ≤ 15 jaar) een sterk verband te vertonen met zeilprestatie. Bij Laser zeilers (i.e. > 15 jaar), echter, vertoonde knie extensie kracht uithouding met oplopende intensiteit (gemeten door middel van de bucket test) een verband met zeilprestatie. De bijdrage van deze knie extensie kracht uithouding blijkt zowel bij Optimist als bij Laser zeilers gerelateerd te zijn aan een uitstel in spiervermoeidheid. Meer nog, bij Laser zeilers blijkt vermoeidheid een sterk verband te vertonen met maximale quadriceps kracht. Deze resultaten suggereren het belang van de implementatie van motorische coördinatie in het fysieke droogtrainingsprogramma bij Optimist zeilers en maximale kracht training in het fysieke droogtrainingsprogramma bij Laser zeilers.

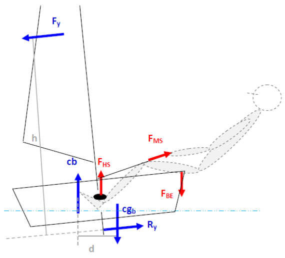
Verder werd ook een zeilemulator ontwikkeld (en biologisch gevalideerd) door gebruik te maken van een biofeedback systeem van de meting van het uithangmoment. Deze zeilemulator stelt ons in staat om een zelf bepaald quasi-isometrisch zeilprotocol op te leggen aan verschillende zeilers of aan dezelfde zeiler op verschillende momenten. Deze innovatieve emulatie ergometer kan geïmplementeerd worden in de zeilspecifieke prestatiediagnostiek en trainingsopvolging bij verschillende type zwaardbootzeilers.

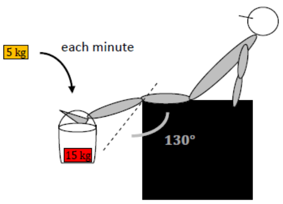
Tijdens submaximale (quasi-)isometrische knie extensie beweging (als deel van de uithangbeweging) bij zowel Optimist en Laser zeilers vertoont de vermoeidheid ter hoogte van de quadriceps spier een significante stijging (gereflecteerd door een daling in mean power frequency en stijging root mean square). Nochtans, na een initiële stijging werd een stabilisatie fase geobserveerd. Dit is mogelijks te wijten aan verschillende compensatie strategieën (zoals overstag gaan, kleine dynamische bewegingen en de alternate-leg-strategy) die zeilers gebruiken om vermoeidheid uit te stellen. Deze compensatie strategieën resulteren in een tijdelijke relaxatie van de quadriceps spier die een snelle uitstroom van gedeoxygeneerd bloed en instroom van geoxygeneerd bloed veroorzaakt. Vergeleken met ongetrainde controles blijken Optimist zeilers een ander patroon van spiervezelrekrutering en zuurstofextractie ter hoogte van de spier te vertonen, waarschijnlijk om vermoeidheid uit te stellen en zodoende de knie extensie kracht uithouding te verbeteren met het oog op een betere uithangprestatie.

PART 1:

GENERAL INTRODUCTION, OBJECTIVES & OUTLINE OF THE DISSERTATION







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Preface

Olympic sailing in Flanders (Belgium) has a tradition of many years' standing. Considering the relative small size of the country, there has been an overrepresentation of Flemish sailors performing at elite level and achieving top results in international competitions (e.g. André Nelis, Jacques Rogge, Sébastien Godefroid, Philippe Bergmans and Evi Van Acker). However, it is debatable whether their performance was the result of a structured follow-up and training system or the consequence of individual talent and personal effort and sacrifices. In order to set up a structured follow-up and training system for sailing in Flanders, it is crucial to enhance our understanding of sailing performance and how to optimize sailing training and racing.

This first part provides a general introduction and a brief acquaintance with several essentials of (dinghy) sailing. Afterwards, we elaborate on the biomechanical aspects of dinghy sailing and discuss the stress put on the sailors' body during dinghy sailing. Further, a state of the art of physiological research in dinghy sailing is presented. Subsequently, we give a thorough presentation of the physical profile of dinghy sailors. The second part of the general introduction presents the methodology used to gain more insight into the physiological mechanisms at the muscle level. Finally, a number of gaps in the current literature, which provide the impetus for the studies conducted within this dissertation, are identified. The general introduction ends with an outline of the research objectives that were pursued through the different studies presented in part 2 of this dissertation.

1. Dinghy sailing

Sailing: what & how

Sailing is a popular water sport that involves a boat moving through the water driven by the wind (acting on the sail according to the principle of Bernoulli). A boat may be sailed either "off-wind", including "running" (E) in the same direction as the wind, "broad reaching" (D) and "beam reaching" (C) across the wind, or it may be sailed "upwind", including "close hauled sailing" (B) (figure 1). Since it is impossible to make any progress sailing directly into the wind (A), sailors use a zigzag pattern to progress to an upwind mark with each "beat" about 30-45° into the wind (B), depending on the sailors' judgment of reaching the upwind mark in the shortest time (Legg et al., 1999). This process of turning the boat through the wind until it blows onto the other side of the sail is called "tacking" and requires the sailor(s) to change boat edge in order to preserve boat balance (Spurway et al., 2007). When sailing downwind, the dinghy is often turned across the wind from one tack to another, with the sail changing side. This method of turning is known as gybing (Legg et al., 1999).

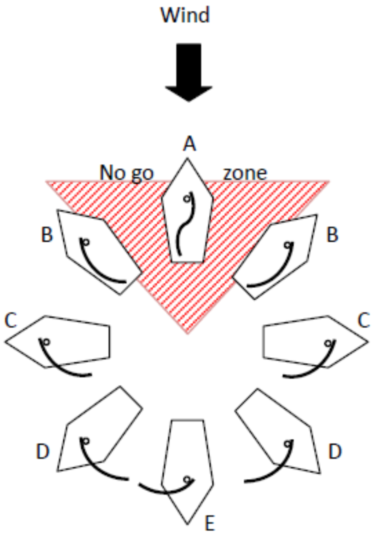


Figure 1: *Sailing courses: (A) into the wind, (B) close hauled, (C) beam reaching, (D) broad reaching, (E) off-wind or running.*

When sailing, sideways wind forces acting on the sail cause a ‘tilting moment’ on the boat (tilting moment = $h \cdot F_y$) (figure 2A). To prevent the boat from capsizing and to optimize boat speed, the sailor has to create a counteracting ‘uprighting moment’ (uprighting moment = $- d \cdot P_{(b+s)}$) (figure 2A). Stronger winds result in a larger tilting moment requiring a counteracting uprighting moment of a comparable size (figure 2B). As illustrated in figure 2B, this is realized by enlarging the moment arm d, whereby the centre of gravity of boat and sailor moves windward while the centre of buoyancy moves leeward (Bojsen-Møller & Bojsen-Møller, 2001). The technique used to accomplish the windward displacement of the centre of gravity of boat and sailor in a one-man boat is a characteristic exercise, known as *hiking*. Hiking is done by hooking the feet under a hiking strap, placing the dorsal side of the thigh on the boat edge and extending the upper body outside the windward side of the boat (Mackie et al., 1999; Ferraris et al., 2010). The posture adopted during hiking varies between having an upright trunk to leaning backwards at increasing angles until the hip is fully extended (Sekulic et al., 2006). The latter ensures a further windward position of the sailor’s body centre of mass, resulting in a larger moment arm of the uprighting moment.

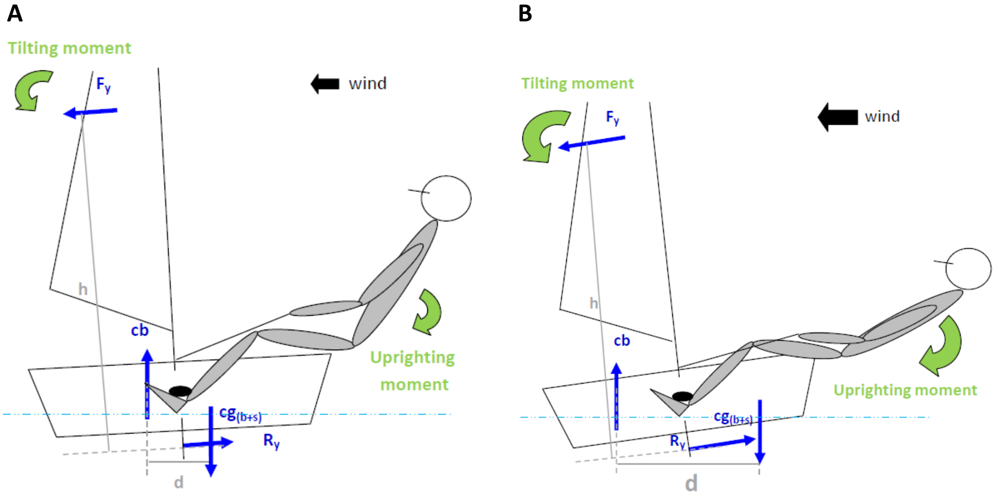


Figure 2: *Dynamics of dinghy sailing: free body diagram of boat + sailor:* F_y *= aerodynamic force, cb = force acting in the centre of buoyancy (i.e. created by the hydrostatic and hydrodynamic lift),* $cg_{(b+s)}$ *= weight of boat and sailor acting at the centre of mass,* R_y *= water resistance, h = distance water resistance - momentary mainsail centre of pressure, d = distance centre of buoyancy - centre of gravity. Tilting moment and uprighting moment are illustrative notations on the figure.* (Bojsen-Møller & Bojsen-Møller, 2001)

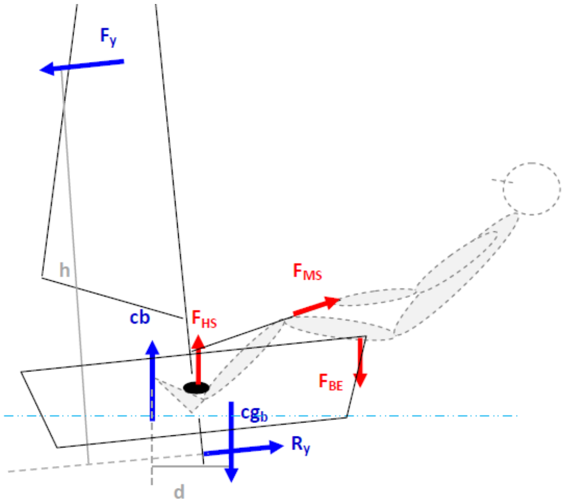


Figure 3: *Free body diagram of boat: cg_b = gravity of boat acting at the centre of mass, F_{HS} = hiking strap forces, F_{MS} = mainsheet forces, F_{BE} = boat edge forces.* (Callewaert & De Ryck, 2009)

While hiking, the sailor creates three forces on the boat: the load on the hiking straps (F_{HS}), the load which results from sitting on the boat edge (F_{BE}) and the load on the mainsheet (F_{MS}) (figure 3).

During a race hikers most of the time hold or pull the mainsheet (i.e. a rope which controls the position of the main sail) in order to gain optimal boat speed. This is called “trimming”. In certain conditions or classes, the sailor vigorously pulls the mainsheet in an action called “pumping”. This action is often associated with the boat descending the leading edge of a wave and is designed to enhance boat speed (Legg et al., 1999). According to the ISAF racing rules, one pump for each wave or wind gust is allowed when surfing or planing (ISAF, 2013). Otherwise it is not allowed, except in the Finn class where pumping is allowed from 10 knots (ISAF, 2013).

Olympic dinghy Sailing

Dinghy sailing is the activity of sailing small boats by using the sails, the rudder, the trim and the side to side balance of the boat. At the 2012 Olympics, the dinghies selected for Olympic racing were the Laser Standard (for men), Laser Radial (for women), Finn (for men), 49er (for men) and 470 (for both men and women) (Ferraris et al., 2010; ISAF, 2012). However, each Olympiad the Olympic boat types are revised and changed when necessary. For instance, the Europe dinghy has been an Olympic dinghy for women from 1992 up to 2004. In 2008, the Europe dinghy was replaced by the Laser Radial. For the 2016 Olympics, the one-person-dinghies will remain equal to the boat types from the 2012 Olympics (i.e. Laser Standard and Finn for men and Laser Radial for women).

The most popular boat types in Flanders are the optimist and the Laser. The optimist dinghy is with its 200.000 members in 100 countries the world-leading youth class (IODA, 2013a). The Optimist class is sailed by both boys and girls up to the age of 15. Once Flemish sailors outgrow the Optimist, many switch to the Europe or Laser dinghy. The Laser can be sailed with several sizes of sails: 4.7 m^2 (Laser 4.7), 5.76 m^2 (Laser Radial) and 7.06 m^2 (Laser Standard).

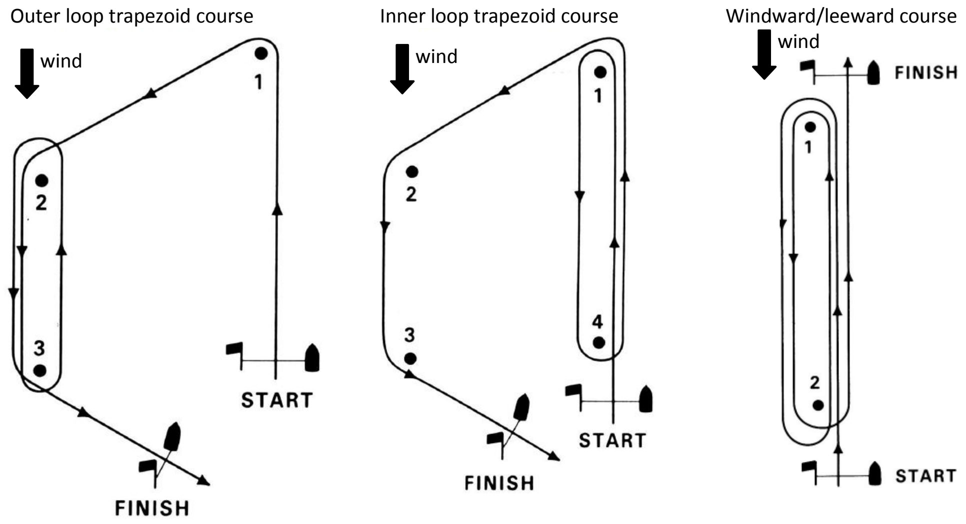
Sailing technique and thus physiological requirements differ among boat types. Based on sailor to yacht weight ratio which influences the hiking exercise, Bojsen-Møller and co-workers (2007) introduced a classification system for Olympic sailors in order to simplify monitoring of physical requirements, facilitate comparisons between different type of sailors and enable sailor-specific training recommendations (Bojsen-Møller et al., 2007). In this classification system, Laser 4.7, Laser Radial, Laser Standard and Europe sailors are identified as ‘dynamic hikers’ because they hike in a very dynamic way due to a high sailor to yacht weight ratio. Static hikers (i.e. Finn and Star sailors), however, are characterized by a rather static hiking manner due to a low sailor to yacht weight ratio (Bojsen-Møller et al., 2007).

1.1. Biomechanical and physiological analysis of dinghy sailing

1.1.1. Biomechanics

Race analysis and movement pattern

To win a dinghy race, the sailor must be the first to finish the sailing course. The outer loop trapezoid course is sailed during optimist regattas (figure 4) (IODA, 2013b) and both the trapezoid (inner and outer loop) and windward/leeward courses are used during Olympic Laser sailing (figure 4) (ISAF, 2012).



Outer loop trapezoid course

Inner loop trapezoid course

Windward/leeward course

Figure 4: *The current competitive course diagrams: the outer trapezoid, inner trapezoid and windward/leeward course* (ISAF, 2012).

In order to finish the sailing course as a winner, sailors attempt to navigate as fast (and during upwind sailing also as straight) as possible to the next buoy in the course. In order to win distance and time, the sailor needs to focus on spotting and utilizing wind shifts and gusts. This use of wind shifts and gusts can result in 8 to 10 % decrease of the distance sailed during the upwind leg (Bojsen-Møller & Bojsen-Møller, 2001).

From a hydrodynamic point of view, an optimal boat balance is an important factor contributing to regatta outcome, because boat speed significantly decreases when the tilting angle (i.e. the angle between the mast deviation and the exact vertical) is more than 10° to 20° (Bojsen-Møller & Bojsen-Møller, 2001). Therefore, sailors carefully need to control the boat in continuously varying wind and wave conditions, including changes in wind speed and direction (Mackie et al., 1999). As a consequence, sailors move not only in dorsal and ventral direction, but also sideward in order to preserve both the lateral (i.e. boat roll) and longitudinal (i.e. boat pitch) balance of the boat (Bojsen-Møller & Bojsen-Møller, 2001). The longitudinal boat balance is important to make the boat plane (i.e. the boat weight is predominantly supported by the hydrodynamic lift rather than hydrostatic lift) so that the boat speed is minimally reduced. Therefore, the sailors twist their upper body (i.e. predominantly an axial rotation of the trunk) to handle the boat through the waves, especially in strong winds.

Results of an international Optimist regatta (in 14 to 16 knots) race analysis indicated an average total racing time of 49 ± 8 min (table 1). Also, 66 ± 9 % of total racing time was spent on sailing upwind (divided over 2 upwind sailing legs) and a 6 s tacking period was reported every 90 ± 25 s and 89 ± 28 s during the first and second upwind leg respectively (Callewaert & De Ryck, 2009).

Table 1: *Race analysis during international Optimist regatta (n=1).* (Callewaert & De Ryck, 2009)

		Total racing time (min)	Time sailing upwind (min)	Upwind sailing time (%)	Hiking time in 1st upwind leg (s)	Hiking time in 2nd upwind leg (s)	Race result (place)
Day 1	Race 1	36	18	50	62	129	9
	Race 2	45	32	71	134	79	12
Day 2	Race 1	52	37	71	99	121	70
	Race 2	57	42	74	79	71	70
	Race 3	47	30	64	92	67	2
Day 3	Race 1	57	39	68	75	69	2
Mean		49 ± 8	33 ± 9	66 ± 9	90 ± 25	89 ± 28	42

To our knowledge, only 2 studies investigated the temporal analysis of the physical activities performed during Laser sailing (Blackburn, 1994; Legg et al., 1999). Findings are related to regattas using the triangle course (figure 5) and therefore can be considered outdated. The results demonstrated that circa 70 % of total racing time (i.e. 3 times 20 min upwind leg duration and 84 min total racing time) was spent on the upwind leg (Blackburn, 1994). In general, the Laser, Europe and Finn sailors spent respectively 94 %, 91 % and 78 % of total upwind leg time on hiking (Legg et al., 1999). Sailors spent more time hiking either upright or extended while trimming the mainsheet than any other activity: on average 46 ± 16 %, 66

± 16 % and 48 ± 24 % of upwind legs was spent hiking upright while trimming the mainsheet and 48 ± 16 %, 25 ± 17 % and 30 ± 17 % of upwind legs was spent hiking extended while trimming the mainsheet in the Laser, Europe and Finn classes respectively (Legg et al., 1999). This analysis also showed that any particular uninterrupted maintenance of hiking posture is seldom more than approximately 15 s (Legg et al., 1999). Hiking is periodically interrupted when tacking, making rig adjustments or sporadic sitting inboard due to brief period of low wind speed. The study of Legg and co-workers (1999) documented a tacking manoeuvre circa every 128 to 174 s, whereas the study of Blackburn (1994) reported a tack every 90 seconds during Laser sailing. One tack lasted on average 9 s, 7 s and 4 s during Laser, Europe and Finn racing respectively (Legg et al., 1999). The analysis also showed that the temporal pattern of Europe and Laser sailors did not differ significantly. The only difference is that Europe sailors seemed to hike more upright (66 ± 16 % versus 46 ± 16 % of the upwind leg) and less extended (25 ± 17 % versus 48 ± 16 % of the upwind leg) as compared to Laser sailors (Legg et al., 1999).

Since the above race analysis in Laser sailing are not applicable to racing time patterns today, Ferraris & colleagues (2010) more recently investigated the racing rules of the 2012 Olympics in London and discussed some important differences with previous research discussed above. Firstly, the triangle course which was used for all the great championships up to the 2012 Olympics was replaced by the trapezoid or windward/leeward course (during medal race). The latter course has a shorter total racing time (on average 30 to 40 min with average upwind leg duration of 15-20 min (Ferraris et al., 2010)). Nevertheless, the 2012 Olympic racing rules indicate a time limit from start line to mark 1 of 30 min (ISAF, 2012) which is similar to earlier time periods spent on the upwind leg (Blackburn, 1994).

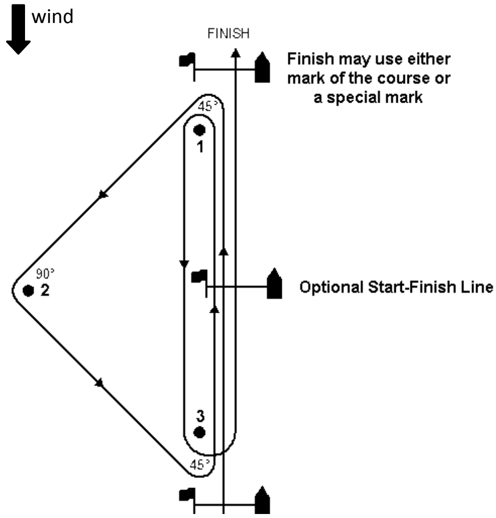


Figure 5: *The Olympic triangle course, used up till the 2012 Olympics.* (ISAF, 2013)

Kinematics

Postures and joint angles during hiking are inherent to the type of boat and its dimensions (table 2). A kinematic analysis of short period on-water optimist hiking (in 8-10 knots) demonstrated a mean knee angle (i.e. angle between the lower leg and upper leg) of 91.0° ± 1.8° and a mean hip angle (i.e. angle between upper leg and upper body) of 97.1° ± 10.4° respectively (Callewaert & De Ryck, 2009). This implies an average range of motion in the hip of 28.4° ± 15.1°. These data also showed a slow frequency in both the knee (0.5 ± 0.2 Hz) and hip (0.4 ± 0.1 Hz) angle variations (Callewaert & De Ryck, 2009). In on-water Laser hiking (8-12 knots), larger average knee (149° ± 3°) and hip (113° ± 12°) angles were observed (Mackie et al., 1999), indicating little range of movement in the knee and a lot of range of motion in the hip.

Table 2: *Reported mean joint angles (± SD) in on-water and simulation studies.*

Study	Sailor (n)	Joint angle Knee (°)	 Hip (°)	Type of study
Callewaert & De Ryck, 2009	OS ♂ (2)	91 ± 2	97 ± 10	o-w (8-10 knots)
Blackburn, 2000	LS ♂ (-)	129	104	o-w (>12knots)
Mackie et al., 1999	LS ♂ (3)	149 ± 3	113 ± 12	o-w (8-12 knots)
Le Deroff & Iachkine, 2001	LS ♂ (2)	158 ± 3	127 ± 20	S (dynamic)

Note: OS = Optimist sailor, LS = Laser sailor, o-w = on-water, S = simulation

In sports science, sport specific postures are often transferred to a standardized laboratory situation for experiments such as simulation studies or sport-specific strength measurements. In such studies, several joint angles have been used to represent the hiking posture (table 3). It should be emphasized that the joint angles in table 2 are outcome variables (i.e. joint angles measured during sailing) whereas the variables in table 3 are input variables (i.e. joint angles used to represent sailing-specific postures).

Table 3: *Reported average joint angles (± SD) during on-water and simulation studies.*

Study	Sailors (n)	Joint angle		Type of study
		Knee (°)	Hip (°)	
Maïsetti et al., 2006	LS ♂ (6)	140	110	S (static)
Boyas et al., 2009	LS ♂ (9)	140	110	S (static)
Aagaard et al., 1998	Sailors	115	100	Strength measurement
Mackie & Legg, 1999	LS ♂ (1)	150	120	Strength measurement
Tan et al., 2006	LS ♂ (15)	130	104	Strength measurement
Bojsen-Møller et al., 2007	Sailors	110	100	Strength measurement
Vangelakoudi et al., 2007	LS ♂ (8)	145		Strength measurement

Note: LS = Laser sailors, S = simulation study. Blank cells indicate unreported data.

Kinetics

During Laser hiking, large uprighting moments, reflected in an uprighting force of 789 ± 38 N, are created (Blackburn, 1994). Several studies quantified the forces applied to the hiking strap, mainsheet and tiller during hiking (Blackburn, 1994; Mackie & Legg, 1999; Mackie et al., 1999). Elite sailors showed an averaged hiking strap force of 715 N (or 87 % predicted MVC) with peaks exceeding 828 N (or 100 % predicted MVC) (Mackie et al., 1999), whereas a non-competitive club sailor showed a mean hiking strap load of 647 N (or 59 % MVC) with peaks up to 843 N (or 77% MVC) (Mackie & Legg, 1999). Elite sailors also demonstrated an average mainsheet load of 162 N (or 27 % predicted MVC) with peaks up to 287 N (or 50 % predicted MVC), whereas a non-competitive club sailor demonstrated a mean mainsheet load of 111 N (or 35 % MVC) with peaks up to 289 N (or 90 % MVC) (Mackie & Legg, 1999). A load of 15 N is generated on the tiller (Blackburn, 1994). Accordingly, the loads in club sailors were reported relatively to maximal voluntary contraction (MVC) intensity performed on a Biodex (Mackie & Legg, 1999), whereas those in elite sailors were reported relatively to the sailors predicted maximal voluntary contraction (MVC) for the knee extensor and elbow flexor. The knee extensor predicted MVC was calculated by multiplying the maximal hiking strap load from a portable hiking bench with 0.47 (because preliminary results indicated that subjects could exert 0.47 ± 0.11 times greater knee extensor strength on a Biodex than on a hiking bench). The elbow flexors predicted MVC was calculated by multiplying the hiking bench maximal contraction with 0.2 (because preliminary results indicated that subjects could exert 0.2 ± 0.07 times greater elbow flexor strength on a Biodex than on a hiking bench) (Mackie et al., 1999).

Muscle activity

To our knowledge, the first study which investigated sailors' muscle activity was the study of Rogge (1972). This study quantified by means of (invasive) needle electromyography (EMG) the activity of different lower body muscles during three different static hiking positions on a Finn deck (at several hip angles). The results revealed a higher load in the M. Rectus Femoris in comparison to the abdominals (Rogge, 1972). More recently, a qualitative movement analysis was conducted and defined 3 different hiking postures: (1) sitting (90°-120° enclosed hip angle), (2) upright hiking (120°-150° enclosed hip angle) and (3) extended hiking (150°-180° enclosed hip angle). Muscle activity was measured in the 3 hiking postures (figure 6) (Sekulic et al., 2006).

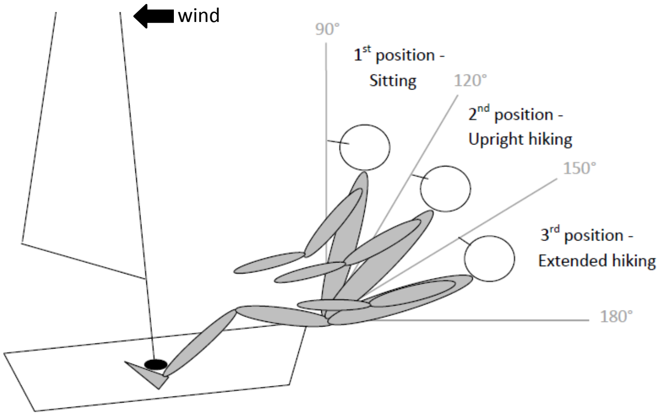


Figure 6: *Different hiking positions based on Sekulic & colleagues (2006).*

The data obtained demonstrated that the quadriceps muscle is the most activated muscle during dinghy sailing (i.e. at 70 to 72 %, 87 to 98 % and 99 to 109 % maximal integrated EMG ($iEMG_{max}$) during 1^{st}, 2^{nd} and 3^{rd} position respectively (figure 6)). The role of the quadriceps muscles is threefold: (1) the M. rectus femoris generates hip flexion to prevent falling backwards, (2) all 4 quadriceps muscle heads generate knee extension force on the hiking straps and (3) the knee stabilization is accomplished by co-contraction with the hamstring muscles (Aagaard et al., 1998; Le Deroff & Iachkine, 2001; Spurway, 2001). The abdominal muscles were exposed to a considerable load during the leaning position (i.e. 52 to 60 % $iEMG_{max}$), whereas no load was put on these muscle in the first position (i.e. 0 to 1 % $iEMG_{max}$) and small load in the second position (i.e. 13 to 16 % $iEMG_{max}$) (Sekulic et al., 2006). Vogiatzis & colleagues (1996) reported during hiking on a dinghy simulator an average M. rectus femoris recruitment of 31 to 39 % $iEMG_{max}$. Musculus iliopsoas contraction maintains trunk flexion (preventing a fall backwards) and the abdominal muscles contract in order to prevent hyperextension in the back and induce trunk core stability (Blackburn, 1994; Spurway, 2001; Sekulic et al., 2006). Aagaard and co-workers (1998) suggested that also the M. quadratus lumborum is recruited in order to stabilize the lower part of the back and the spine. However, the data of Sekulic & colleagues (2006) did not support this suggestion (i.e. 0 to 5 % $iEMG_{max}$). Similarly, this study did not show much M. tibialis anterior recruitment (i.e. 1 to 2 % $iEMG_{max}$) to induce dorsiflexion in the ankle joint (Sekulic et al., 2006), although some authors suggested so (Maïsetti et al., 2002a; Ferraris et al., 2010). The M. tensor fasciae latae will act as a hip flexor and also as a hip abductor, making sideways movement possible (Maïsetti et al., 2002a). In addition, the upper body limbs activity is often underestimated. Sailors constantly need to trim during sailing (Mackie & Legg, 1999) and will therefore put considerable load on the upper body muscles like the M. sternocleidomastoïdeus, M. pectoralis, M. biceps brachii, M. brachioradialis, etc. (Ferraris et al., 2010)

In conclusion, race analysis and temporal movement patterns show that performance during the upwind leg is both from temporal, technical/tactical and physical point of view contributing to the regatta outcome. Hiking is a critical phase during dinghy racing (Legg et al., 1999; Bojsen-Møller & Bojsen-Møller, 2001). It is also known that “hiking is hard” (Spurway, 2007). Hiking is a bilateral and multi-joint movement which generates large stress in the anterior muscles that cross the knee and hip joint (Vogiatzis et al., 1995; Maïsetti et al., 2006; Sekulic et al., 2006). Therefore, it is interesting to take a closer look at the energy delivery during this hiking exercise.

1.1.2. Physiology

1.1.2.1. Cardiorespiratory, -vascular and metabolic responses

To determine the energetic cost of hiking exercise, several physiological parameters have been investigated. The following tables (4 to 8) give an overview of the parameters registered in the different kinds of studies: on-water and simulation studies. It should be emphasized that the reported responses are highly dependent on the type of study (i.e. on-water or simulation studies), the wind and weather conditions (in on-water studies), the time pattern (e.g. frequencies of manoeuvres), the methodology of the measurements (e.g. direct or indirect measurements) and the expertise level of the sailors (Spurway, 2007).

Generally, simulation studies often show a lower energetic cost, due to a lower or different kind of energetic demand, as for example static hiking simulation versus dynamic hiking simulation or on-water hiking. Heart rate (HR) and oxygen uptake (VO_2) measurements during on-water upwind sailing range from 124 to 168 beats·min^{-1} (table 4) and 39 to 68 % VO_2peak (table 6) respectively. These responses are slightly higher compared to measurements during simulated upwind sailing which range from 112 to 156 beats·min^{-1} (table 5) and from 20 to 30 % VO_2peak (table 6) respectively. Blood pressure is only measured during simulation studies (table 7). Lactate concentration ([La]) turns out to be somewhat lower during on-water hiking ([La] = 2.3 to 3.3 mmol·l^{-1}) compared to simulated hiking ([La] = 2.3-4.5 mmol·l^{-1}) (table 8). This suggests that static indoor simulation of the hiking task does not reflect the true nature of on-water hiking (Cunningham & Hale, 2007).

Table 4: *Mean heart rate (HR) measurements (± SD) during on-water upwind sailing.*

Study	Sailors (n)	Light wind (4-9 knots) (beats·min^{-1})	Moderate wind (10-16 knots) (beats·min^{-1})	Strong wind (16-30 knots) (beats·min^{-1})	Protocol
Rodio et al., 1999	OS ♂ (9)	129 ± 14			3 x 5 min upw s
Callewaert & De Ryck, 2009	OS ♂ (2)		158 ± 5		Upw s in regatta
De Vito et al., 1996	LS ♂ (4)	144 ± 21			15 min upw s
Castagna & Brisswalter, 2007	LS ♂ (8)	124			30 min upw s
Castagna et al., 2004	LS ♂ (8)		132		30 min upw s
Vogiatzis et al., 1995	LS ♂ (8)		145 ± 21		10 min upw s
Von Pudenz et al., 1981	LS ♂ (-)		143 ± 9	168 ± 12	Upw s in regatta
Cunningham, 1996	LS ♂ (8)	132 ± 12	158 ± 11	165 ± 8	Upw s in regatta

Note: OS = optimist sailors, LS = Laser sailors, upw s = upwind sailing. Blank cells indicate unreported data.

Table 5: *Mean heart rate (HR) measurements (± SD) during simulated upwind sailing.*

Study	Sailors (n)	Mean HR (beats·min^{-1})	Mean HR (% HR$_{peak}$)	Protocol
Vogiatzis et al., 1993	LS ♂ (8)	126 ± 15		2 hiking actions to exhaustion with 15 s interval
Blackburn, 1994	LS ♂ (10)	118 ± 25	62 ± 13	20 min simulated upw s
Vogiatzis et al., 1996	LS ♂ (8)	112 ± 6		4 x 3 min simulated static hiking with 15 s interval
Felici et al., 1999	LS ♂ (7)	138 ± 17		15 min hiking at 60 % of maximal hiking torque
Felici et al., 1999	LS ♂ (7)	141 ± 13		3 min hiking at 85 % of maximal hiking torque
Cunningham & Hale, 2007	LS ♂ (6)	156 ± 8	85	30 min simulated upw s
Vogiatzis et al., 2008	LS ♂ (8)	136 ± 13		5 x 3 min simulated hiking with 5 s interval
Vangelakoudi et al., 2007	LS ♂ (8)	149 ± 22		4 x 3 min simulated static hiking with 5 s interval

Note: LS = Laser sailors, upw s = upwind sailing. Blank cells indicate unreported data.

Table 6: *Mean oxygen uptake (VO$_2$) measurements (± SD) during both on-water and simulated upwind sailing.*

Study	Sailors (n)	Mean VO$_2$	% VO$_2$peak	Protocol (wind)
Rodio et al., 1999	OS ♂ (9)	25 ± 1 ml·min^{-1}·kg^{-1}	59 %	3 x 5 min o-w upw s (8-12 knots)
Vogiatzis et al., 1995	LS ♂ (8)	20 ± 3 ml·min^{-1}·kg^{-1}	39 %	10 min o-w upw s (7-20 knots)
De Vito et al., 1996	LS ♂ (8)	23 ml·min^{-1}·kg^{-1}	44 %	15 min o-w upw s (5-8 knots)
Castagna et al., 2004	LS ♂ (9)		54.5 %	30 min o-w upw s (< 18 knots)
Castagna & Brisswalter, 2007	LS ♂ (13)		68.4 %	30 min o-w upw s (< 15 knots)
Blackburn, 1994	LS ♂ (10)	1.12 ± 0.22 l·min^{-1}	25 ± 5 %	20 min simulated upw s (10 LS)
Felici et al., 1999	LS ♂ (7)	0.87 ± 0.11 l·min^{-1}		15 min simulated hiking at 60 % HT$_{max}$
Felici et al., 1999	LS ♂ (7)	0.95 ± 0.21 l·min^{-1}		3 min simulated hiking at 85 % HT$_{max}$
Vogiatzis et al., 1996	LS ♂ (8)	1.04 ± 0.05 l·min^{-1}		5 x 3 min simulated hiking 5 s interval
Cunningham & Hale, 2007	LS ♂ (6)	2.51 ± 0.24 l·min^{-1}		30 min simulated upw s
Vogiatzis et al., 2008	LS ♂ (8)	13.7 ± 1.6 ml·min^{-1}·kg^{-1}		5 x 3 min simulated hiking 5 s interval

Note: o-w = on-water, OS = optimist sailors, LS = Laser sailors, HT$_{max}$ = maximal hiking torque, upw s = upwind sailing. Blank cells indicate unreported data.

More windy weather conditions demonstrated a greater cardiorespiratory demand. Vogiatzis & colleagues (1995) observed disproportional VO$_2$ and HR increases in relation to different wind velocities. During on-water upwind sailing, VO$_2$ and HR increased significantly up to about 40 % VO$_2$peak and 75 % HR$_{peak}$ respectively (Vogiatzis et al., 1995; De Vito et al., 1996) (table 4 & 6). This disproportional VO$_2$/HR relationship reflects the tension put on the anterior muscles (Vogiatzis et al., 1995), largely comparable to the classical observations during isometric exercise (Goodwin et al., 1972; Lind, 1983). It is well known that during isometric effort greater than 20 % MVC, the resistance to blood flow in the muscular vascular bed increases (Lind, 1983). As a consequence, both HR and blood pressure (BP) rises in an attempt (of the body) to enhance perfusion through the working muscles which is probably restricted due to an increased intramuscular pressure (Vogiatzis et al., 1995; Marchetti, 2001; Spurway, 2001). When muscular contraction is higher than 50 % MVC, muscle perfusion is completely restricted (i.e. ischemia) (Lind, 1983). As a consequence, not only HR and BP increases, but also several metabolic byproducts accumulate in the interstitial tissue (Lind, 1983; Marchetti, 2001). To date, blood pressure (BP) has only been measured in laboratory settings. The systolic BP increases up to 172-195 mmHg due to an increased peripheral resistance and the diastolic BP increases up to 100-117 mmHg to compensate the increased intrathoracic pressure (table 6). The mean arterial blood pressure (MAP) during simulated upwind sailing (at the same heart rate and oxygen uptake as during on-water hiking) significantly increases up to 127 ± 3 mmHg (Rodio et al., 1999) and 129 ± 16 mmHg (Vangelakoudi et al., 2007) in Optimist and Laser sailors respectively (table 7). In addition, hyperventilation during hiking is indicated by the disproportionate high increase in ventilation (up to on average 50 to 63 $l \cdot min^{-1}$) in relation to VO_2-increase (Vogiatzis et al., 1995; De Vito et al., 1996). Both above mentioned observations also reflect the presence of an isometric component in the hiking exercise (Goodwin et al., 1972). In contrast, this disproportional VO_2/HR relationship and hyperventilation is not seen in the study of Castagna & colleagues (2007).

Table 7: *Mean blood pressure (BP) measurements (mmHg) (± SD) during simulated upwind sailing.*

Study	Sailors (n)	Mean systolic BP (mmHg)	Mean diastolic BP (mmHg)	Protocol
Blackburn, 1994	LS ♂ (10)	172 ± 18	100 ± 14	20 min simulated upw s
Felici et al., 1999	LS ♂ (7)	183 ± 12	117 ± 12	15 min hiking at 60 % of HT_{max}
Felici et al., 1999	LS ♂ (7)	195 ± 21	110 ± 21	3 min hiking at 85 % of HT_{max}
Vogiatzis et al., 2008	LS ♂ (8)	195 ± 18		5 x 3 min simulated hiking 5 s interval

Note: LS = Laser sailors, HT_{max} = maximal hiking torque, upw s = upwind sailing. Blank cells indicate unreported data.

It should be noticed that the lower VO_2-values recorded in the studies of De Vito & co-workers (1996) and Vogiatzis & colleagues (1995), compared to the studies of Castagna & co-workers (2004 and 2007) (table 6) may be explained by differences in the experimental protocol. The studies first mentioned (Vogiatzis et al., 1995; De Vito et al., 1996) reported sailing durations up to 15 min. Compared to the results of Castagna & colleagues (2007) over a similar time span (i.e. at T10), they were in agreement with each other. Furthermore, the subjects had to tack every 2 min (Castagna & Brisswalter, 2007) whereas in the study of Vogiatzis (1995) and De Vito (1996) the protocol was one of continuous upwind sailing. This suggests that tacking contributes to a momentary recovery from the intensive hiking effort (Castagna & Brisswalter, 2007).

The double product (i.e. systolic BP x HR) is of particular interest to judging the cardiac load which is in Laser hiking three times higher than at rest (Marchetti, 2001). This augmented double product indicates a relevant myocardial efficiency, disproportional to the energy cost of the exercise (Marchetti, 2001). Moreover, also cardiac output (Q) seems to double with respect to the resting values: 7 ± 1 versus 3.9 ± 0.4 $l \cdot min^{-1}$ (Rodio et al., 1999) and 10.4 ± 1 versus 5.9 ± 0.6 $l \cdot min^{-1}$ (Felici et al., 1999) during Optimist and Laser hiking respectively.

Table 8: *Mean blood lactate concentration ([La]) measurements (± SD) during both on-water and simulated upwind sailing.*

Study	Sailors (n)	[La] ($mmol \cdot l^{-1}$)	Protocol (wind)
Vogiatzis et al., 1995	LS ♂ (8)	2.3 ± 0.8	10 min on-water upw s (7-20 knots)
Castagna et al., 2004	LS ♂ (9)	2.77	30 min on-water upw s (< 18 knots)
Castagna & Brisswalter, 2007	LS ♂ (13)	3.3	30 min on-water upw s (< 15 knots)
Vogiatzis et al., 1993	LS ♂ (8)	4 ± 1.5	3 bouts of simulated hiking 15 s rest
Blackburn, 1994	LS ♂ (10)	2.32 ± 0.81	20 min simulated upw s
Felici et al., 1999	LS ♂ (7)	3.1 ± 1.1	15 min hiking at 60 % of HT_{max}
Felici et al., 1999	LS ♂ (7)	3.9 ± 0.7	3 min hiking at 85 % of HT_{max}
Vogiatzis et al., 1996	LS ♂ (8)	2.4	5 x 3 min simulated hiking with 5 s interval
Cunningham & Hale, 2007	LS ♂ (6)	4.47 ± 0.94	30 min upw s
Vogiatzis et al., 2008	LS ♂ (8)	3.0 ± 0.6	5 x 3 min simulated hiking with 5 s interval

Note: LS = Laser sailors, HT_{max} = maximal hiking torque, upw s = upwind sailing. Blank cells are unreported data.

The respiratory exchange ratio (RER) increases up to 0.98 ± 0.11 (Felici et al., 1999), indicating that aerobic energy delivery is predominant during exhaustive on-water hiking (Castagna & Brisswalter, 2007). Also, the average blood lactate concentration ([La]) seems to remain quite low (table 8) and rarely exceeds 4 $mmol \cdot l^{-1}$ suggesting that acidosis is not the limiting factor in maintaining this hiking position. It should also be argued that the lactate produced by dynamic arm activity (in strong winds) can be shuttled to the legs, taken up by the best-adapted fibers of the second region (mainly the oxidative-glycolytic fibers), converted back to pyruvate and taken into the mitochondria as a supplementary metabolite (Gladden, 2000; Miller et al., 2002; Easton et al., 2007).

Based on the physiological responses during hiking, it could be suggested that hiking is an isometric exercise. However, the dynamic component is in the opinion of several scientists clearly not to be neglected (Spurway, 2001). Therefore, the term “Quasi-isometric exercise” (Spurway, 2001, 2007) is used to indicate that although the muscles are continually making small adjustments to their length, the cardiorespiratory and metabolic responses are nearly similar to those during isometric exercise, but do not reflect a pure isometric contraction (Spurway, 2001, 2007). During hiking, the muscle perfusion is probably not totally restricted (Vogiatzis et al., 2008).

It could be noted that several studies presented the data obtained on the water (VO_2, HR) relatively to treadmill test values (VO_2peak, HR_{peak}) (Castagna & Brisswalter, 2007). To our knowledge, there is no significant information available on the relation between VO_2 recorded on a treadmill and VO_2 on the water. But Astrand & Rodahl (1986) suggest that measurement recorded in the laboratory is not always transferable to field work, especially when muscle actions are different. It appears that the energy cost measured on-water corresponds to 1/3 to 1/2 of the maximal aerobic power of the subjects (Marchetti, 2001). This emphasizes that hiking depends mainly on an aerobic energy delivery. However, at higher intensities (e.g. start of the race (Ferraris et al., 2010)), an additional anaerobic component (inherent to the hiking intensity) can occur. It is assumed that the strenuous quasi-isometric quadriceps contraction which appears to impose on average 40 to 50 % of the total oxygen demand (Spurway, 2007), will probably cause a high intramuscular pressure resulting in a partially restricted muscle perfusion causing an oxygen deficit and thus a more glycolytic energy delivery indicating a greater anaerobic component (Spurway, 2007). However, given the relatively low [La], the consensus view is that the anaerobic component is never dominant (Spurway et al., 2007).

The only study which compared the cardiorespiratory responses to hiking exercise for different levels of sailors showed that the high-skilled sailors indicated higher energy expenditure compared to the low-skilled sailors (Castagna & Brisswalter, 2007). This could be explained by a more dynamic style of hiking, reflected by the low moderate positive relationship ($r = 0.39\text{-}0.41$; $p < 0.05$) between the variability of force exerted on the hiking straps and the energy expenditure (i.e. VO_2) (Blackburn, 1994). Research also suggested that this greater energy expenditure could be due to a higher muscular activation level of the lower leg muscles (Vogiatzis et al., 1993).

To conclude**,** hiking is physiologically considered an intermittent bilateral quasi-isometric contraction recruiting mainly the quadriceps muscle at a submaximal intensity (i.e. 30 to 40 % MVC). This hiking exercise demands principally an aerobic metabolism with increasing share of the anaerobic energy metabolism, dependent on the type of boat, weather and wind conditions, exercise duration, frequency of manoeuvres performed, and skill level of the sailor (Vogiatzis et al., 1995; Castagna & Brisswalter, 2007). It is also known that hiking is hard work and in though conditions fatiguing and even painful (Spurway, 2001). The above section suggests that acidosis is probably not the main contributor to this fatigue development. Therefore, we suggest to thoroughly investigate the muscular responses to hiking exercise.

1.1.2.2. Muscular responses

Several researchers in the field of sailing physiology reached consensus that the main locus of fatigue development is located in the quadriceps muscle, and more specifically in the knee extensor M. vastus lateralis (Sekulic et al., 2006; Spurway, 2007), suggesting that the quasi-isometric exercise performed in this muscle contributes to fatigue (Vogiatzis et al., 1993; Marchetti, 2001; Maïsetti et al., 2006).

Vogiatzis & colleagues (1993) were the first to use surface electromyography (sEMG) to obtain an insight into the cause of fatigue during hiking. He described a decrease in median frequency (MDF) (i.e. an indication of motor unit fire frequency) and an increase in root mean square (RMS) (i.e. an indication of motor unit recruitment) (Vogiatzis et al., 1993). Later on, the neuromuscular mechanisms in the quadriceps muscle during bilateral sustained submaximal isometric knee extension exercise till exhaustion at 50 % MVC on a hiking ergometer were investigated and showed a significant higher endurance time for hikers compared to controls (Maïsetti et al., 2006; Boyas et al., 2009). This difference was explained by the training adaptations sailors develop throughout sailing practice. The first explanation is that sailors are specialized in the intermuscular coordination during hiking, addressing less the more fatiguing muscles which postpones the recruitment of fresh motor units (i.e. increase in RMS). Secondly, this could also be explained by sailors' specialization in intramuscular coordination, recruiting especially slow-twitch fibers and to a lower extent fast-twitch fibers, postponing fatigue development. These two mechanisms contribute to a delayed drop in muscle force and muscular fatigue (Maïsetti et al., 2006; Boyas et al., 2009). However, the limited level of RMS (44 % RMS_{max} and 54 % RMS_{max} for hikers and controls respectively) at exhaustion suggests that fatigue during hiking is not related to a maximal motor unit recruitment (Boyas et al., 2009).

Since research assumes that quadriceps blood perfusion is partially restricted, Vogiatzis & colleagues (2008) investigated the muscles hemodynamics by means of near infrared spectroscopy (NIRS) during five 3 min hiking bouts interspersed by 5 min of rest on an isometric hiking ergometer. A reduced tissue oxygenation to approximately 60 % at the beginning of each hiking bout (Vogiatzis et al., 2008), followed by a steady state throughout the rest of the bout, indicates that an equilibrium point was reached (De Blasi et al., 1993). As suggested, oxygen deficit did not accumulate because compensation strategies were used during hiking: (1) counter-movements in the lower body (i.e. quasi-isometric contraction) and (2) short periods of active recuperation (as tacking, alternate-leg-use technique and dynamic movements in the upper body). These strategies were used to overcome the consequences of blood flow occlusion or restriction and increase their possibilities for physical performance. Spurway (2007) reported even a 50 % higher limb blood flow and VO_2 during quasi-isometric contraction compared to pure isometric contraction at 20% MVC intensity on an isokinetic dynamometer (Spurway, 2007). However, these mechanisms still appear to be insufficient to meet the requirements of the increased metabolic demand. It is suggested that these dynamic counter movements add even more to the energy demand than they restore the blood flow. Additionally, brief periods of active recuperation, as tacking and alternate-leg-use strategy, activate muscle blood flow to restore the oxygen delivery to the muscle (Spurway, 2007). A half-time recovery of the tissue oxygenation of 8 ± 2 s was observed (Vogiatzis et al., 2008). This small reoxygenation rate is known to be more influenced by muscle oxygen demand than by oxygen supply. This suggests that the oxidative status of the quadriceps muscle was adequately preserved (Vogiatzis et al., 2008). In contrast, a later study of Vogiatzis and co-workers which combined NIRS-recordings with blood flow index recordings during the same hiking protocol (i.e. 5 times 3 min hiking on an isometric hiking ergometer, interspersed by 5 min of rest) showed that quadriceps muscle blood flow increased only slightly and deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) increased significantly (Vogiatzis et al., 2011). Thus, the results were in line with previous findings (Blackburn, 1994; Vogiatzis et al., 1996, 2008; Spurway, 2007) suggesting that the progressive reduction in quadriceps muscle oxygen availability during hiking arises from reduced blood flow (Vogiatzis et al., 2011). As a consequence, there is a reduced oxygen delivery to this muscle resulting in the onset of muscle fatigue (Vogiatzis et al., 2011).

1.2. Profile of dinghy sailors

As a sport, sailing is unique in combining high level physical activities with a knowledge of aero- and hydrodynamics, navigation and meteorology, racing rules and tactics, and an ability to anticipate events and to make fast well-considered decisions (Bojsen-Møller & Bojsen-Møller, 2001). In this context, the anthropometric profile and physiological fitness are of great importance for sailing performance because *hiking is hard*.

1.2.1. Anthropometric profile

The righting moment that is generated while hiking is a function of the sailor's body weight and its position relative to the centre-line of the boat (i.e. body height) (Blackburn & Hubinger, 1995). It seems that a bigger sail which induces the tilting moment will require a heavier and/or taller sailor in order to enable boat control. Therefore, optimal anthropometric and physiological requirements differ between boat classes (Plyley et al., 1985).

Up to the age of 15, young boys and girls all compete together in the Optimist class. The dimensions of the Optimist dinghy (2.31m long, 1.13m wide, 35 kg of boat weight and 3.5 m^2 sail surface) induce an optimal body weight (i.e. 45 to 50 kg) and height (i.e. 160 to 165 cm) to perform in this dinghy (IODA, 2013a) (table 9). This boat type is sailed by boys and girls together because of the minor physiological differences before maturation. The optimist dimensions and thus also the optimal body morphology induce that children who are early maturing, outgrow this boat before the age of 15 years, keeping competition fair.

Table 9: *Overview of the mean age, body height and body weight (± SD) and age, body height and body weight range of elite Optimist sailors competing in the world championships in 2002, 2003, 2007 and 2011.*

Study	n	Age (years)	Age range (years)	Height (cm)	Height range (cm)	Weight (kg)	Weight range (kg)	Sailing level
IODA, 2002	10		12-15	159.8 ± 6.9	149-170	46.3 ± 4.9	40-54	2002 WT 10
Gonzalez Munoz, 2003	16	13.9		159.8		48.6		2003 WT 20
IODA, 2007	10 (2♀,8♂)	14.6 ± 0.7	13-15	161.5 ± 3.8	155-166	47.3 ± 4.5	41-54	2007 WT 10
IODA, 2011	10 (1♀,9♂)	14.3 ± 0.8	13-15	165.7 ± 5.7	158-175	49.7 ± 4.3	44-58	2011 WT 10

Note: WT = world top. Blank cells indicate unreported data.

In literature, more anthropometric data can be found for adult sailors (figure 7, 8, 9 & 10). Age turns out to be similar in dynamic hikers, static hikers and boardsailors (figure 7).

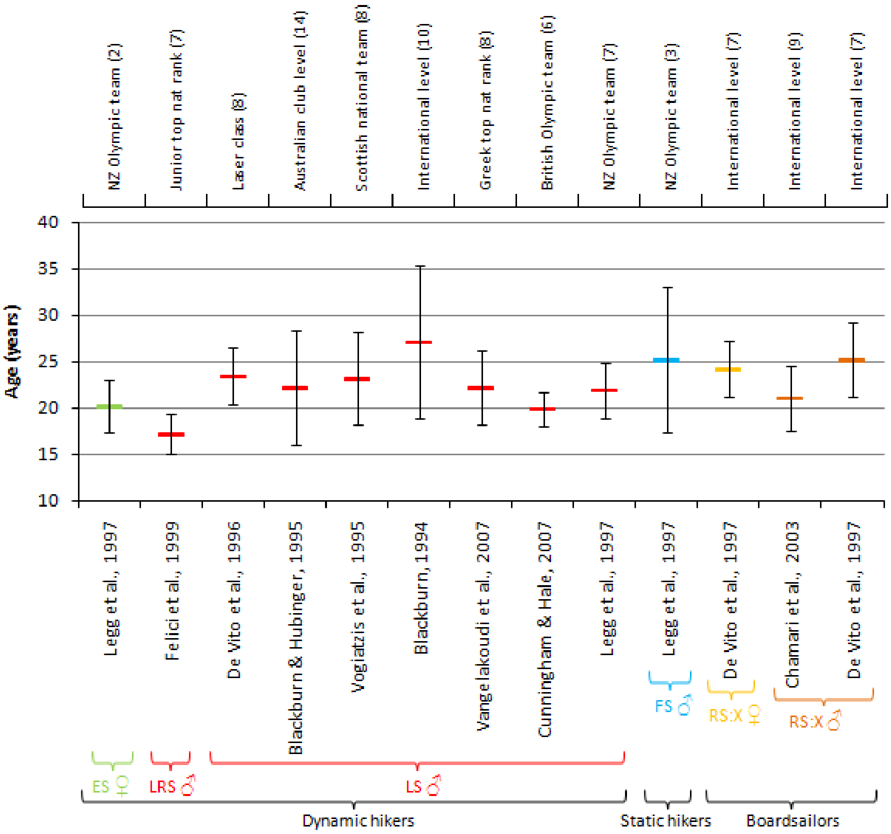


Figure 7*: Overview of the mean age (± SD) or range of adult female and male dynamic hikers, static hikers and boardsailors).*

Note: NZ = New Zealand, nat = national, ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, FS = Finn sailors.

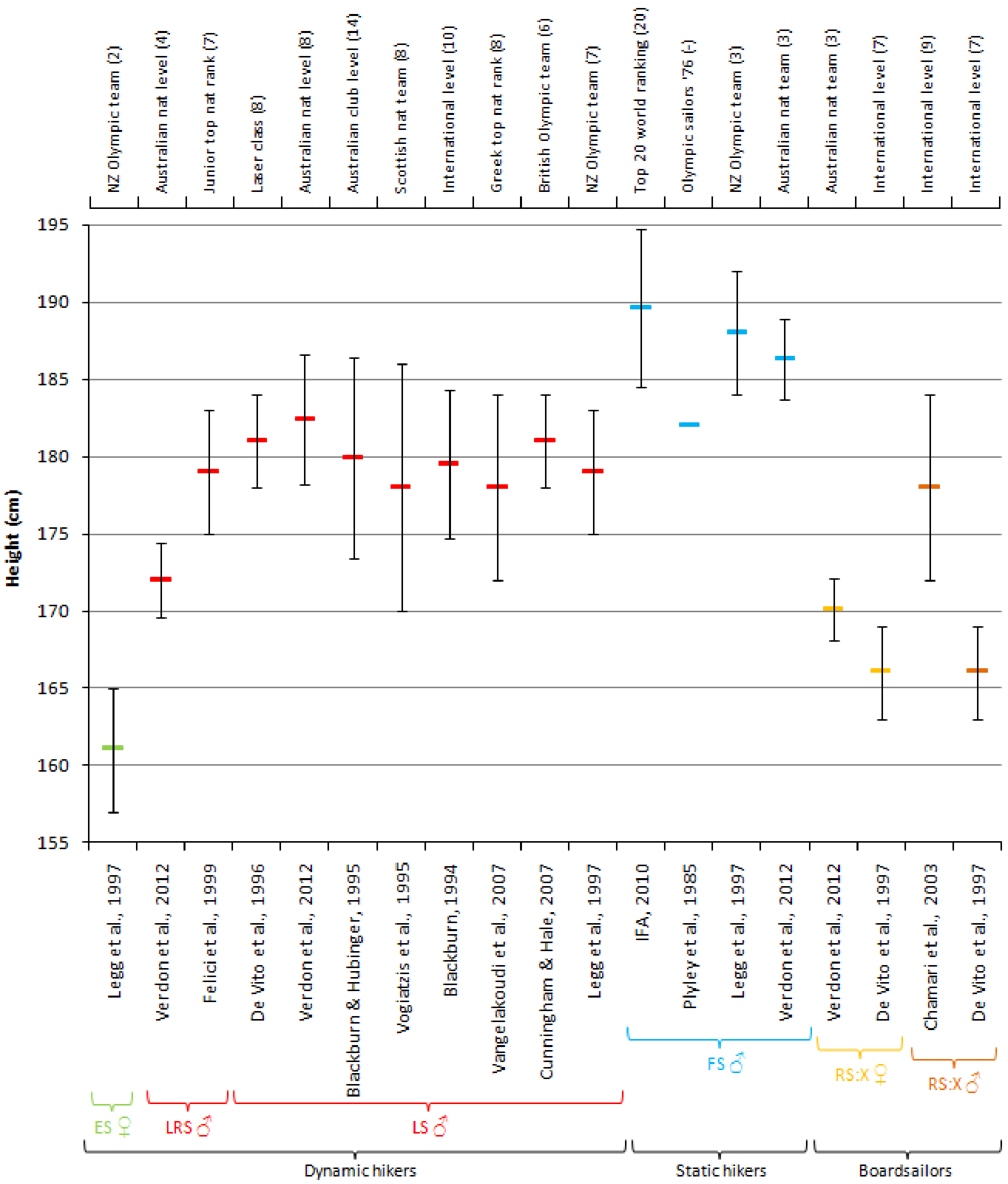


***Figure 8**: Overview of the mean body height (± SD) or range of adult female and male dynamic hikers, static hikers and boardsailors. Note:NZ = New Zealand, nat = national, ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, FS = Finn sailors.*

Static hikers (i.e. Finn sailors) are taller (figure 8) and heavier (figure 9) than the dynamic hikers (i.e. Europe, Laser Radial and Laser sailors), because they sail in larger and heavier boats. Although the static hikers are taller and heavier than the dynamic hikers, they are still too light weighted in comparison to their boat mass resulting in a more static hiking pattern. In comparison to adult sailors, board sailors (i.e. RS:X) are in general smaller (figure 8) and lighter (figure 9). Body fat in static hikers seems higher than in dynamic hikers (figure 10). This is probably related to the higher body weight that static hikers need in order to control their boat movement.

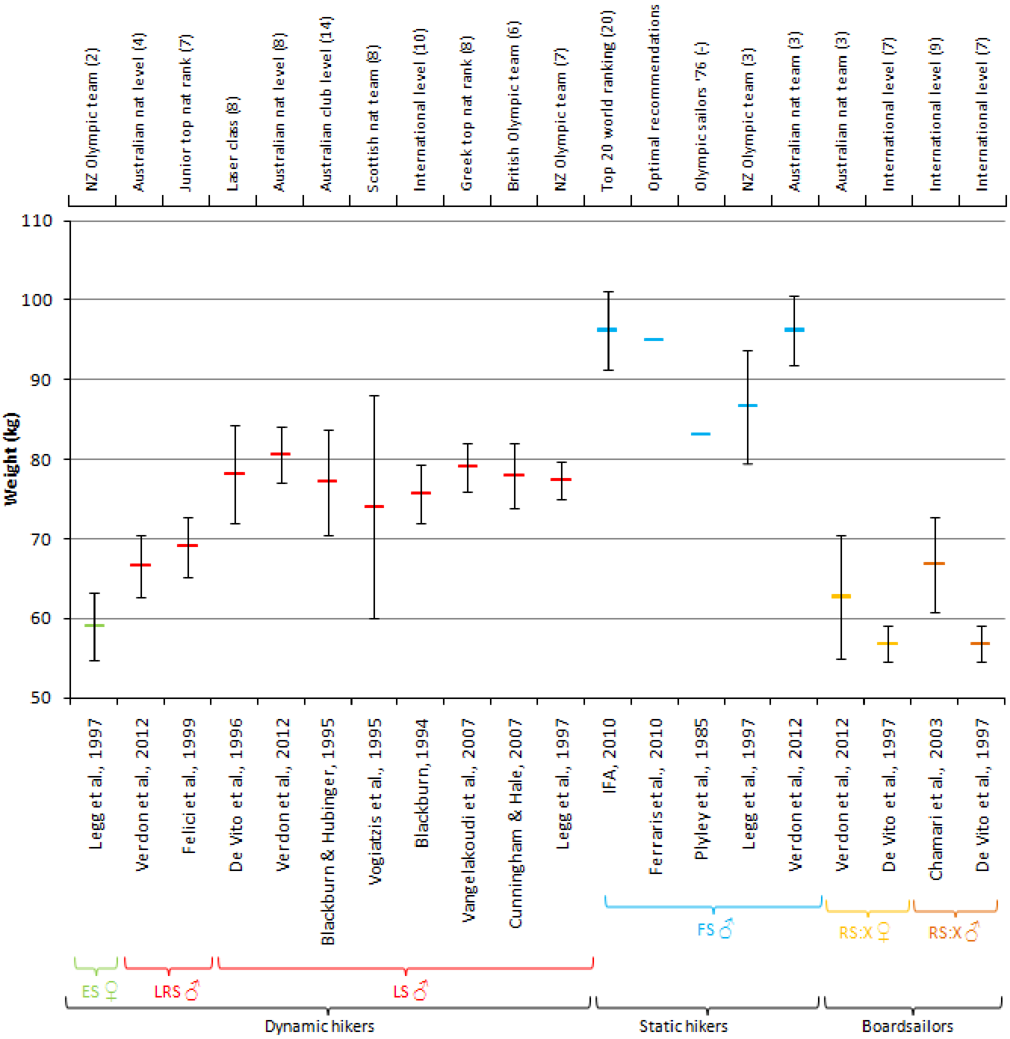


***Figure 9**: Overview of the mean body weight (± SD) or range of adult female and male dynamic hikers, static hikers and boardsailors (i.e. RS:X). Note: NZ = New Zealand, nat = national,ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, FS = Finn sailors.*

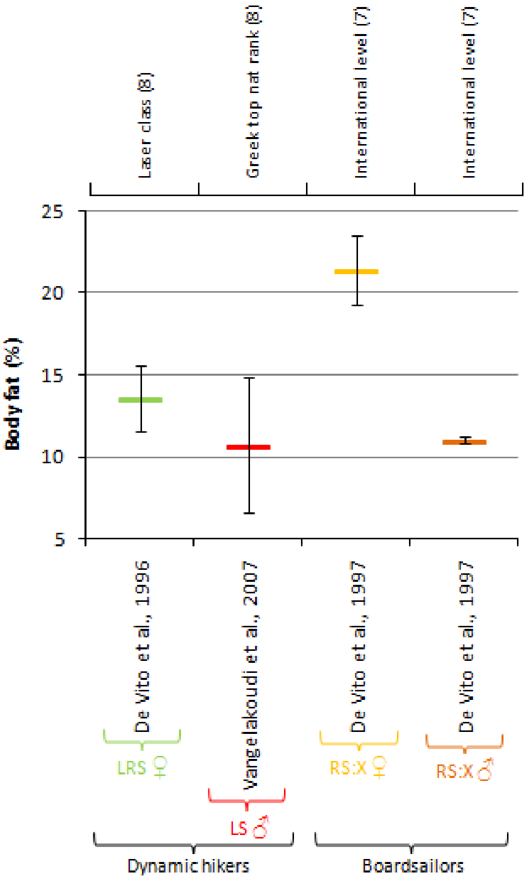


Figure 10*: Overview of the mean body fat (± SD) or range of adult female and male dynamic hikers, static hikers and boardsailors (i.e. RS:X). Note: nat = national, ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, FS = Finn sailors.*

Several results towards the importance of anthropometrical determinants for sailing performance are reported in literature. Tan & colleagues (2006) found a strong negative correlation between body weight and sailing performance ($r = -0.69$; $p < 0.05$) in Laser sailors, whereas the study of Blackburn & Hubinger (1995) observed only a negligible correlation ($r = 0.18$; $p < 0.05$). Also, Plyley & colleagues (1985) suggested that it is rather the body proportions that are important for optimal sailing performance. Therefore, he suggested that the successful sailors should be light and tall and have a high centre of gravity. To date, no strong evidence has been found to confirm this theory (Plyley et al., 1985; Legg et al., 1997). Yet, it should be noted that in practice anthropometric measurements determine a sailors' boat type (table 10).

***Table 10:** Overview of optimal recommendations for body height, body weight and body fat for adult sailors.*

Study	Sailors (n)	Height (cm)	Weight (kg)	Body fat (%)
Blackburn, 2000	ES ♀ (4)	165-180	64-71	
Blackburn, 2001	LRS ♀ (-)		65-72	
Fletcher, 2008	LRS ♀ (-)	166-176	66-68	20-26
Ferraris et al., 2010	LRS ♀ (-)		55-70	
Blackburn, 2000	LS ♂ (38)	176-188	80-84	
Blackburn, 2001	LS ♂ (-)		78-83	
Fletcher, 2008	LS ♂ (-)	178-188	78-82	10-12
Ferraris et al., 2010	LS ♂ (-)		72-83	
Blackburn, 2000	FS ♂ (2)	175-190	88-96	
Blackburn, 2001	FS ♂ (-)		95-110	
Fletcher, 2008	F S ♂ (-)	180-196	95-106	12-20
Ferraris et al., 2010	FS ♂ (-)		± 95	
Blackburn, 2001	RS:X ♀ (-)		52-59	
Blackburn, 2001	RS:X ♂ (-)		65-70	

Note: ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, FS = Finn sailors, RS:X = surfers
Blank cells indicate unreported data.(-) = number not available.

1.2.2. Physiological profile

As the physiological analysis of a dinghy regatta suggested a main aerobic energy delivery, it is necessary to take a closer look at the physiological profile of sailors (Spurway, 2001).

There is only one study which investigated the physical profile of Optimist sailors (Rodio et al., 1999). The peak oxygen uptake was calculated according to the extrapolation method (on a running treadmill) and appeared to be 42 ± 3 ml·kg^{-1}·min^{-1} with a maximal heart rate of 196 ± 6 beats·min^{-1} (Rodio et al., 1999). At the maximal level, elite male dynamic hikers exhibit an absolute and relative peak O_2-uptake of 4.3-4.7 l·min^{-1} and 50-60 ml·min^{-1}·kg^{-1} respectively (table 11). This relative peak oxygen uptake is more or less comparable to that of male static hikers, however the absolute maximal oxygen uptake is somewhat lower than that of static hikers, due to the higher body weight of the static hikers which is absolutely vital for performance (Bojsen-Møller et al., 2007). Female sailors showed a lower peak oxygen uptake compared to their male colleagues (table 11). Board sailors showed clearly a higher peak oxygen uptake (i.e. between 60 and 70 ml·min^{-1}·kg^{-1} in male RS:X and 49.2 ± 4.1 ml·min^{-1}·kg^{-1} in female RS:X) in comparison to static and dynamic hikers (table 11). This is probably due to the pumping technique which is unlimited in boardsailing, in contrast to sailing. This pumping technique makes this discipline aerobically more challenging with a partial involvement of the anaerobic metabolism (De Vito et al., 1997). The relative VO_2peak-values from male sailors are comparable to those of male elite athletes in team sports such as football (55-65 ml·min^{-1}·kg^{-1}) (Boone et al., 2012), basketball (50 - 60 ml·min^{-1}·kg^{-1}) (Boone & Bourgois, 2013), handball (55-60 ml·min^{-1}·kg^{-1}) (Sporis et al., 2010), tennis (58.5 ± 9.4 ml·min^{-1}·kg^{-1}) (Bergeron et al., 1991)and ice-hockey (50 - 60 ml·min^{-1}·kg^{-1}) (Quinney et al., 2008). Moreover, very high aerobic power (e.g. at the level of elite runner and/or cyclists: 70-90 ml O_2·kg^{-1}) is not required for success in sailing (Larsson et al., 1996; Bojsen-Møller et al., 2007). Although Blackburn & Hubinger (1995) showed a moderate correlation between an aerobic fitness field test and the subjects regatta performance, more recent studies suggest that this good cardiorespiratory fitness is not directly related to hiking performance (Vogiatzis et al., 1995; Tan et al., 2006; Bojsen-Møller et al., 2007), but is indirectly necessary to induce a good recovery and to sustain the large training load during periods of intense training (Bojsen-Møller & Bojsen-Møller, 2001).

Table 11: *Overview of mean peak oxygen uptake, peak heart rate and VO_2threshold (± SD) recordings from sailors.*

Study	Sailors (n)	VO_2peak (l·min^{-1})	VO_2peak (ml·min^{-1}·kg^{-1})	HR_{peak} (bts·min^{-1})	VO_2 Tvent (% VO_2peak)	Protocol	Sailing level
Rodio et al., 1999	OS ♂ (9)		42 ± 3	208 ± 1		Incr run	
Bojsen-Møller et al., 2007	ES ♀ (6)	3.26 ± 0.26	47.3 ± 4.9	189 ± 8		Max cst run	Danish OT
Blackburn, 1994	LS ♂ (10)	4.71 ± 0.62	62.3	189 ± 12		Ramp arm-leg	internat level
Vogiatzis et al., 1995	LS ♂ (8)		52.0 ± 6.0	196 ± 6		Incr cycl	Scottish NT
De Vito et al., 1996	LS ♂ (8)		53.4 ± 3.5	184 ± 9	72	Incr cycl step	Laser class
Portier & Guézennec, 2002	LS ♂ (8)		55.0 ± 4.6			Incr cycl step	French sailors
Castagna et al., 2004	LS ♂ (9)		59.9 ± 5.2	204 ± 10		Incr cycl step	Internat level
Castagna & Brisswalter, 2007	LS ♂ (13)		58.2 ± 4.7	192 ± 4	57.3 ± 3.2	Incr run steps	internat level
Cunningham & Hale, 2007	LS ♂ (6)	4.32 ± 0.16	55.6 ± 4.0	183 ± 8		cycl step test	British OT
Bojsen-Møller et al., 2007	LS ♂ (8)	4.68 ± 0.31	58.3 ± 4.2	193 ± 8		Max cst run	Danish OT
Bojsen-Møller et al., 2007	FS/Star ♂ (5)	4.41 ± 0.26	47.6 ± 3.5	197 ± 4		Max cst run	Danish OT
Bojsen-Møller et al., 2007	FS ♂ (4)	5.6 ± 0.1	63.3 ± 2.4	182 ± 9		Max cst run	Danish OT
De Vito et al., 1997	RS:X ♀ (7)	2.8 ± 0.3	49.2 ± 4.1	184 ± 8	61.0	Incr cycling	Internat level
Chamari et al., 2003	RS:X (9♂,1♀)		62.5 ± 9.2	194 ± 10	74.1 ± 5.1	Incr run	Internat level
De Vito et al., 1997	RS:X ♂ (7)	4.5 ± 0.3	63.6 ± 2.3	185 ± 16	67.9	Incr cycl	Internat level

Note: VO_2 Tvent = ventilatory threshold, OS = Optimist sailors, ES = Europe sailors, LS = Laser sailors, FS = Finn sailors, max = maximal, cst = constant, incr = incremental, cycl = cycling, nat = national, OT = Olympic team, NT = national team. Blank cells indicate unreported data.

At submaximal level, one study in Laser sailors indicated a ventilatory threshold at a high percentage of VO_2peak (i.e. 72 % VO_2peak) (De Vito et al., 1996), while another study showed a very low ventilatory threshold (i.e. 57.3 % VO_2peak) (Castagna & Brisswalter, 2007). Further, board sailors demonstrated a ventilatory threshold and an anaerobic threshold both at a high percentage of VO_2peak (i.e. 74.1 ± 5.1 and 88.3 ± 5.7 % VO_2peak respectively) (Chamari et al., 2003) (table 11).

To our knowledge, literature contains no values of peak power during incremental exercise tests. Nevertheless, the study of Vangelakoudi & colleagues (2007) showed in Laser sailors a maximal and mean anaerobic power of 10.5 ± 1.2 $W \cdot kg^{-1}$ and 8.0 ± 0.8 $W \cdot kg^{-1}$ measured during a 30 s Wingate test with a load of 7.5 % body weight respectively. The maximal values were only slightly lower than those of swimmers (11.1 ± 1.06 $W \cdot kg^{-1}$) and similar to those of water polo players (10.7 ± 0.2 $W \cdot kg^{-1}$) and middle-distance runners (10.5 ± 0.1 $W \cdot kg^{-1}$) (Inbar et al., 1996). The mean values were similar to team sport athletes (8.2 ± 0.1 $W \cdot kg^{-1}$) and long-distance runners (8.0 ± 0.2 $W \cdot kg^{-1}$) (Inbar et al., 1996). This indicates that Laser sailors have a rather well-developed anaerobic power, probably necessary to apply large forces to the hiking straps in choppy and gusty conditions (Vangelakoudi et al., 2007). Furthermore, this study also indicated a very strong correlation between ranking and maximal and mean power output on the Wingate anaerobic test ($r = -0.83$ and $r = -0.71$ respectively; $p < 0.05$) (Vangelakoudi et al., 2007), indicating that both indices are important determinants of sailing performance in Laser class sailing (Vangelakoudi et al., 2007). Also, the fatigue index (FI) was calculated as the percentage decrease in power output during the 30 s test (Inbar et al., 1996) and appeared to be 42 ± 5 % for better sailors in comparison to 49 ± 6 % in club sailors. A significant lower FI for national top-ranked sailors compared to club sailors, suggests that better sailors have a better capacity to resist fatiguing contractions (Vangelakoudi et al., 2007).

The aerobic fitness described above is based on laboratory tests that are very accurate but often expensive. Therefore, field tests are often used to register the development of the aerobic and anaerobic power of the athlete. Three field tests often used in sailors to reflect their maximal aerobic power and endurance are the distance rowed in 4 min, in 12 min and the time to row 2500 m (Legg et al., 1997). The data in table 12 show that static sailors (i.e. Laser Standard and Finn sailors) have better scores on all 3 tests in comparison to the dynamic and board sailors, indicating the higher absolute aerobic power of the static sailors (Legg et al., 1997).

Table 12: *Overview of several field tests reflecting aerobic capacity used for sailors.*

Study	Sailors (n)	Distance in 4 min rowing (m)	Distance in 12 min rowing (m)	Time for 2500m rowing (min)	Sailing level
Legg et al., 1997	ES ♀ (2)		2538 ± 250	11.89 ± 1.15	New Zealand OT
Verdon et al., 2012	LRS ♂ (3)	1047 ± 32			Australian NT
Legg et al., 1997	LSS (7)		3231 ± 107	9.35 ± 0.31	New Zealand OT
Verdon et al., 2012	LSS (7)	1173 ± 47			Australian NT
Legg et al., 1997	FS (3)		3339 ± 49	9.08 ± 0.17	New Zealand OT
Verdon et al., 2012	FS (3)	1175 ± 42			Australian NT
Verdon et al., 2012	RS:X ♀ (3)	1026 ± 58			Australian NT

Note: ES = Europe sailors, LRS = Laser Radial sailors, LSS = Laser Standard sailors, FS = Finn sailors, OT = Olympic team, NT = national team. Blank cells are unreported data.

1.2.3. Strength profile

Since single dinghy sailors spend 94 % of the upwind leg on the exhaustive hiking exercise (Legg et al., 1999), it is considered that this exercise is of great importance for the regatta outcome. Accordingly, three studies demonstrated that sailing performance is significantly related to hiking endurance time, each measured by a different test (Blackburn & Hubinger, 1995; Tan et al., 2006; Vangelakoudi et al., 2007). The first and most frequently used method to measure hiking endurance is the bucket test (Blackburn & Hubinger, 1995; Tan et al., 2006; Verdon et al., 2012) (figure 11 and table 13). The bucket test is an incremental quadriceps knee extension strength endurance test where subjects sit on a padded bench with the back of the thigh bent over one edge of the bench. A steel bucket with a padded strap attached in place of the handle (total mass 0.7 kg (Blackburn & Hubinger, 1995) or 1.4 kg (Tan et al., 2006)) is hung over the ankles. The test begins with a 15-kg plate placed in the bucket. The subjects have to maintain a knee angle of > 130° (the angle between the tibia and the bench was checked every 60 s using a goniometer) as 5kg-plates are added to the bucket each minute until the subject can no longer hold the bucket at the prescribed angle (Blackburn & Hubinger, 1995) (figure 11).

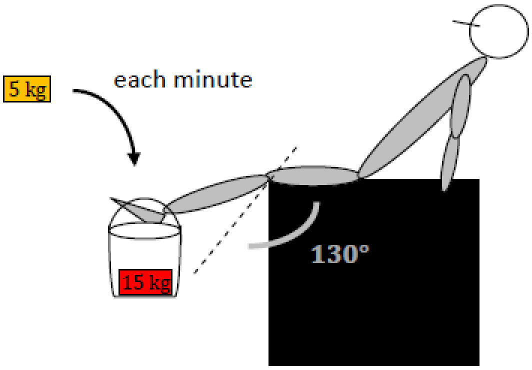


Figure 11: *Schematic outline of the Bucket test.*

The very strong positive correlation (r = 0.82; $p < 0.05$) between the sailors' on-water performance and the score on the bucket test supports the validity of this test and the importance of hiking endurance for sailing performance (Blackburn & Hubinger, 1995). Although Vangelakoudi & colleagues (2007) found no significant relation between ranking and endurance time performing hiking exercise on a Laser simulator, they found a strong positive correlation (r = 0.62; $p < 0.05$) between ranking and the time to exhaustion during an isometric knee extension strength endurance exercise on an isokinetic dynamometer (at 45 % MVC). Also, Tan & co-workers (2006) found no significant correlation between ranking and bucket test, but they observed a strong negative correlation between ranking and the maximal hiking moment over 3 min (i.e. HM_{180}) (r = -0.62; $p < 0.05$) (i.e. measured on a hiking bench mounted onto a force platform). In combination with the very strong correlation (r = 0.81; $p < 0.05$) between HM_{180} and 3-RM knee extension strength, this suggests the importance of maximal quadriceps strength to improve hiking endurance (Tan et al., 2006). Blackburn & Hubinger (1995) revealed a strong positive correlation between ranking and maximal isometric knee extensor strength (r = 0.60; $p < 0.05$), confirming the impact of maximal isometric knee extension strength on sailing performance.

Table 13: *Overview of performance on the bucket test (± SD).*

Study	Sailors (n)	Bucket test (s)	Protocol	Sailing level
Tan et al., 2006	LS ♀ (18)	221 ± 41	Bucket mass = 1.4 kg + 5 kg·min^{-1}	National level
Blackburn & Hubinger, 1995	LS ♂ (13), ♀ (1)	379 ± 95	Bucket mass = 0.7 kg + 5 kg·min^{-1}	National level
Tan et al., 2006	LS ♂ (37)	291 ± 83	Bucket mass = 1.4 kg + 5 kg·min^{-1}	National level

Note: LS = Laser sailors

Aagaard & colleagues (1998) investigated the relationship between hiking endurance and maximal knee extensor, knee flexor, trunk extensor and flexor strength by using the isokinetic dynamometer. Hiking endurance was related to maximal isometric ($r = 0.67$; $p < 0.05$) and eccentric knee extensor strength ($r = 0.67$; $p < 0.05$) (Aagaard et al., 1998). As already indicated by the movement analysis, the hikers frequently make small-amplitude dynamic movements to avoid the occlusion of muscle blood flow associated with high isometric quadriceps contraction force and to compensate for motions caused by the waves and the wind. As a result, the hiker is frequently exposed to significant amounts of eccentric quadriceps loading. Thus, the high maximal eccentric quadriceps strength may certainly be a training adaptation to frequent hiking practice. Although, it cannot rule out that strength training may have contributed as well (Aagaard et al., 1998).

Aagaard & co-workers (1998) also reported similar maximal strength of both sailors and non-sailors, suggesting that training in hiking develops more strength endurance than force production. Since HM_{180} ($r = 0.62$; $p < 0.05$) and 3RM knee extension strength ($r = 0.47$; $p < 0.05$) showed significant correlations with racing score (Tan et al., 2006), it is suggested that the development of maximum strength reduces the relative isometric load of hiking, allowing a better tolerance and continuation of the quasi-isometric activity. This reflects the relative importance of developing maximal strength in the hiking muscle during off-water practice. Since the importance of maximal strength for Laser sailors was shown (Tan et al., 2006), several studies have tested maximal isometric strength on an isokinetic dynamometer (table 14). The average maximal isometric strength of sailors turns out to range between 300 to 400 N·m, dependent on the knee and hip angles used (table 14). Based on the nature of the hiking postures (previously described), it is clear that hikers encounter large forces across the involved joints (Mackie et al., 1999). Especially in the knee joint where large forces are generated in the quadriceps muscle, often in combination with a lower hamstring contraction, resulting in an imbalanced knee stress (Aagaard et al., 1997, 1998; Bojsen-Møller et al., 2007).

Table 14: *Mean isometric knee extension strength (± SD), measured on an isokinetic dynamometer.*

Study	Sailors (n)	Knee (°)	Hip (°)	Strength (N·m)	Methodology	Sailing level
Aagaard et al., 1998	S ♀ (6)	115	100	228 ± 31	≠ trials, 30-90 s R	Danish OT
Blackburn, 1994	LS ♂ (10)	129	104	270 ± 42	3 trials	International level
Blackburn & Hubinger, 1995	LS (13♂,1♀)	130		249 ± 4		Australian club level
Tan et al., 2006	LS ♂ (37)	130	104	400 ± 76	3 x 6s, 60 s R	National level
Vangelakoudi et al., 2007	LS ♂ (8)	145	120	166 ± 25	2 trials	Greek top rank
Aagaard et al., 1998	S ♂ (15)	115	100	323 ± 58	≠ trials, 30-90 s R	Danish OT
Bojsen-Møller et al., 2007	S ♂ (7)	110	100	369 ± 61	≠ trials, 30-90 s R	Danish OT

Note: S = sailors, LS = Laser sailors, ≠ = several, R = rest, OT = Olympic team. Blank cells indicate unreported data.

During active quadriceps contraction the contribution of antagonist hamstring co-contraction forces are likely to result in a reduction in the anterior-posterior shear forces whereas an increase in the bone-on-bone stress forces acting at the knee joint (Baratta et al., 1988). To evaluate the isometric knee joint stability, isokinetic hamstring/quadriceps ratio (H/Q) is by convention calculated as maximal hamstring contraction strength relative to maximal quadriceps contraction strength for a given angular velocity and contraction mode (isometric, dynamic or eccentric) (Kannus, 1994). The isometric H/Q ratio (at 70° knee flexion) for male and female sailors was 0.34 ± 0.06 and 0.29 ± 0.05 respectively (Bojsen-Møller et al., 2007), whereas the same tests for volleyball and table tennis players resulted in values of 0.46 and 0.44 respectively. This isokinetic H/Q ratio offers no vital information on the muscle potential for dynamic stabilization during actual knee joint movements (Kannus, 1994). Therefore, a functional H/Q ratio (i.e. maximal eccentric hamstring to concentric quadriceps strength) was introduced (Aagaard et al., 1995). As such, a H/Q ratio deficit was observed for hikers (Aagaard et al., 1997; Bojsen-Møller et al., 2007). The functional H/Q ratio at $30°\cdot s^{-1}$ for male and female sailors was 0.53 ± 0.07 and 0.53 ± 0.05, whereas the same tests demonstrated a value of 0.65 in volleyball players and 0.66 in table tennis players (Bojsen-Møller et al., 2007).

Other than the quadriceps strength capacities, also abdominal, lower back, hamstring and upper body strength turns out to be contributing to sailing performance, but to a lesser extent (Bojsen-Møller & Bojsen-Møller, 2001). The maximal concentric strength of the trunk flexor and extensor stabilizes lower back and spine, which seems to have a significant importance for hiking performance of top-level Laser sailors (Aagaard et al., 1998).

Blackburn & Hubinger (1995) developed another sailing specific field test: the sheeting test. The sheeting test consists of a 2 min maximal one-handed sheeting effort (10 times one arm, 10 times other arm, etc.) on a rowing ergometer. The average sheeting power registered in 14 Laser sailors was 114.0 ± 24.1 Watt. Although, this test is not very frequently used, the strong relationship ($r = 0.77$; $p < 0.05$) between sheeting power and sailor's on-water performance suggests strong potential in the physical assessment of dinghy sailors. However, one should refine the test with respect to the involvement of the trunk so that the technique used matches the different sailors' on-water sheeting action (Blackburn & Hubinger, 1995).

Other field tests used to register strength abilities in sailors are handgrip strength (reflecting absolute maximal static body strength), sit-ups, pull-ups (reflecting relative maximal body strength) and push-ups (Plyley et al., 1985; Legg et al., 1997). Good strength of both hands is needed to effectively adjust sail controls. As expected, handgrip strength was significantly related to the subjects' sailing performance ($r = 0.71$; $p < 0.05$) (Blackburn & Hubinger, 1995). It is thought that this handgrip strength is developed in the course of the sailors' sailing practice and, if involved in weight-training, the grip is strengthened whenever the exercises involve gripping a bar or handle. However, handgrip strength is also an indication of absolute maximal static body strength, reflecting the importance of strength in general for sailing performance. Furthermore, table 15 also shows higher handgrip strength (i.e. 62.3 kg) for static sailors compared to dynamic hikers (i.e. 54 kg) and board sailors (i.e. 50 kg), indicating that static hikers have more absolute maximum strength than dynamic hikers, due to the type of boat and their greater muscle mass (Blackburn & Hubinger, 1995). Also, static hikers (i.e. Finn sailors) seem to have similar pull-up (or also called chin-ups) scores and higher sit-up scores compared to the dynamic hikers (i.e. Europe and Laser sailors) (table 15). The similar pull-up scores suggest that static hikers possess a similar relative (pulling strength) but a higher absolute (pulling) strength, probably due to the higher forces they have to bear in the mainsheet (due to greater sail area). Static hikers also have higher push-up scores (i.e. relative to body weight) and sit-up scores compared to dynamic hikers (table 15).

Table 15: *Overview of several field tests reflecting strength used for sailors.*

Study	Sailors (n)	Handgrip (kg)	Sit-ups (nr)	Pull-ups (nr)	Push-ups (nr)	Sailing level
Legg et al., 1997	ES ♀(2)		46 ± 5 ^	1± 1 ^^	19 ± 1 ^^	New Zealand NT
Verdon et al., 2012	LRS ♂ (3)			6 ± 2 ^^^		Australian NT
Blackburn & Hubinger, 1995	LS (13♂,1♀)	54 ± 11				Nat level
Verdon et al., 2012	LSS (7)			13 ± 4 ^^^		Australian NT
Legg et al., 1997	LSS (7)		59 ± 8 ^^	12 ± 5 ^^	39 ± 12 ^^	New Zealand NT
Legg et al., 1997	FS ♂ (3)		67 ± 5 ^^	12 ± 2 ^^	46 ± 9 ^^	New Zealand NT
Plyley et al., 1985	FS ♂ (3)	62.3	62 ^			Olympics sailors '76
Verdon et al., 2012	FS ♂ (3)			13 ± 5		Australian NT
Verdon et al., 2012	RS:X ♀ (3)			10 ± 3		Australian NT
Plyley et al., 1985	BS (-)	50.3	49 ^			Olympics sailors '76

Note: ES = Europe sailors, LRS = Laser Radial sailors, LS = Laser sailors, LSS = Laser Standard sailors, FS = Finn sailors, BS = Board sailors, ^ = within 1 min, ^^ = within 2 min, ^^^ = no time limit, NT = national team. Blank cells indicate unreported data.

Based on the correlations between sailing performance and several physical field test parameters (i.e. bucket test ($r = 0.82$; $p < 0.05$), sheeting power ($r = 0.77$; $p < 0.05$), handgrip strength ($r = 0.71$; $p < 0.05$), maximal knee extension strength ($r = 0.60$; $p < 0.05$), aerobic fitness ($r = 0.46$; $p < 0.05$) and body weight ($r = 0.18$; $p < 0.05$)), Blackburn & Hubinger (1995) outlined a model which described the physical contributors to dinghy sailing performance (figure 12). Although, this model shows a good overall picture, the physical part should be explored more thoroughly. To date, there is no consensus on the determinants of hiking performance and the optimal guidelines for dry-land training (Spurway, 2001), especially for youth sailors.

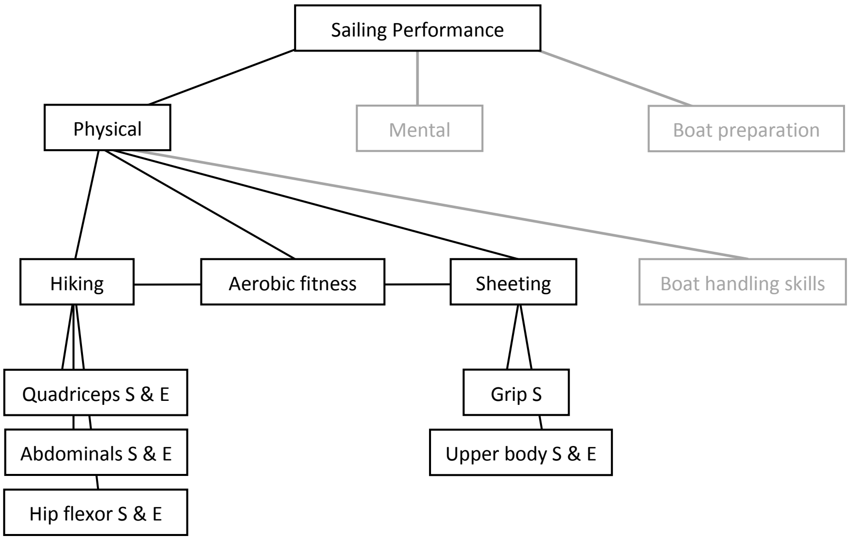


Figure 12: *"Basic physical factors in dinghy sailing" model* (Blackburn & Hubinger, 1995). *(S = strength, E = endurance)*

1.2.4. Other factors

In addition to the anthropometric, physiological and strength components of physical fitness, other factors might also contribute to sailing performance. Bojsen-Møller & Bojsen-Møller (2001) suggested the importance of coordination skills and agility for sailing performance. Although one assumes that these skills are related to sailing technique and are only enhanced by sailing practice, experts suggest that general not-sailing-related coordination and agility exercises (like jumps, leaps, gymnastics, aerobics, yoga, stretching, ball games, etc.) can also improve sailing performance (Bojsen-Møller & Bojsen-Møller, 2001). It is also suggested that flexibility could induce advantage for optimal sailing performance (Legg et al., 1997). Blackburn and Hubinger found a mean score of 14.0 ± 9.2 cm for male Laser sailors on the validated sit-and-reach test (Blackburn & Hubinger, 1995), whereas Pulur (2011) found 29.76 ± 4.77 cm and 32.45 ± 5.07 cm for male and female collegiate sailors.

2. Measurements of muscular responses

In order to get a better insight into the determinants and mechanisms of hiking, the local responses at the level of the quadriceps muscle are thoroughly investigated during sustained submaximal (quasi-) isometric contraction. For this purpose, two technologies were used: surface electromyography (sEMG) and near infrared spectroscopy (NIRS). Below, an overview on the principles and functioning of the equipment as well as the typical response of the obtained parameter to sustained submaximal (quasi-) isometric hiking exercise is presented.

2.1. Electromyography (EMG)

In the early times of sport science, needle EMG was used to investigate muscle activity (Rogge, 1972). Nowadays, surface EMG (sEMG) is used to make a non-invasive recording of the electrical signals that are sent from motoneurons to muscle fibers (i.e. action potentials) while they propagate along the sarcolemma, from the neuromuscular junction to the extremities of the muscle fibers (Enoka, 2008). The classical configuration for sEMG of a whole muscle consists of two small electrodes positioned on the skin over the muscle (De Luca, 1997; Rainoldi et al., 2004). From the sEMG recordings, power spectrum analysis and amplitude calculation of the sEMG can be performed.

Power spectrum analysis is determined by applying a fast Fourier transform to the raw sEMG signal (Petrofsky & Lind, 1980; Macintosh et al., 2006). This outcome parameter is called the mean power frequency (MPF) or median frequency (MDF) (Petrofsky & Lind, 1980) and reflects the motor unit firing rate which shifts towards lower frequencies during fatigue (De Luca, 1997; Vøllestad, 1997; Masuda et al., 1999; Adam & De Luca, 2003; Coburn et al., 2005; Cifrek et al., 2009). Therefore, MPF or MDF can be used as an indication of muscle fatigue in isometric contraction (Merletti et al., 1991; Mannion & Dolan, 1996; Merletti & Roy, 1996; Phinyomark et al., 2012). MPF is an average frequency, calculated as the sum of the product of the power spectrum and the frequency, divided by the total sum of the power spectrum. MDF, however, is a frequency at which the power spectrum is divided into two regions with equal amplitude. The behavior of both is observed to be similar (Phinyomark et al., 2012). Research suggests two reasons for the shift in frequency spectrum to lower frequencies as a result of muscle fatigue. Firstly, a decrease in the muscle fiber conduction velocity as a consequence of local metabolic changes in the working muscle (Bigland-Ritchie et al., 1986; Brody et al., 1991). Secondly, a change in motor unit firing statistics, such as synchronization of the firing rates (Mills & Edwards, 1984; Gabriel & Kamen, 2009). Moreover, such a shift has been found to be related to the relative roles of type I and type II fibers (Ebenbichler et al., 1998).

The rectification and integration of the raw sEMG-signal is called the Root Mean Square (RMS) and provides useful information on the motor unit activity (Calder et al., 2008; Cifrek et al., 2009). Since a linear increase in sEMG activity as a function of work rate was observed (Petrofsky & Lind, 1980), RMS is considered to reflect the recruitment of additional motor units as work rate increases (Farina et al., 2004).

The recordings of MPF and RMS in the quadriceps muscle during submaximal and maximal contractions show good validity (Petrofsky et al., 1982; De Luca, 1997; Rainoldi et al., 2004), reliability ($r = 0.77$-0.92; $p < 0.05$) and reproducibility ($r = 0.73$-0.93; $p < 0.05$) (Viitasalo & Komi, 1975; Ebenbichler et al., 1998). But also the limitations of sEMG recording have been recognized for several decades. On its way from the muscle membrane up to the electrodes, the sEMG signal can be influenced by several external factors altering its shape and characteristics. First of all, the tissue characteristics play an important role. While the human body is a good electrical conductor, the electrical conductivity varies with tissue type, thickness, physiological changes and temperature (Petrofsky & Lind, 1980; Rainoldi et al., 2004). However, the influence of these factors can be minimized by accurate preparation (according to SENIAM recommendations) and execution of the measurements and processing of the raw sEMG signal following the measurements (Stegeman & Hermens, 1999; Rainoldi et al., 2004). Due to the high individual variety in the force of the sEMG signal, normalization of the MPF and RMS to either the MPF or RMS at the maximal voluntary contraction (MVC) (De Luca, 1997; Crenshaw et al., 2010) or the MPF or RMS at the baseline exercise is highly recommended (Mirka, 1991; Crenshaw et al., 1997; Maïsetti et al., 2006; Boyas et al., 2009).

During sustained submaximal isometric contractions, MPF (as an indication of muscle fatigue) decreases and RMS (as an indication of motor unit recruitment) increases

(Crenshaw et al., 1997, 2010; Masuda et al., 1999; Coburn et al., 2005). This pattern is considered to represent fatigue development during sustained submaximal isometric contractions. Fatigue is generally defined as 'a loss of maximal force generating capacity' (Bigland-Ritchie et al., 1986; Vøllestad, 1997). However, during submaximal contraction, it is possible to maintain the torque acceptable constant, in a macroscopic sense, but there are time-dependent physiological and biochemical processes that microscopically alter the means for generating force (De Luca, 1997). These electromyographic sEMG responses during sustained submaximal isometric contraction have already been investigated in different studies, indicating that the rate or pattern of MPF-decrease and RMS-increase is highly dependent on contraction intensity (Zwarts & Arendt-Nielsen, 1988; Brody et al., 1991; Fallentin et al., 1993; Crenshaw et al., 1997; De Ruiter et al., 2007; Boyas & Guével, 2011), type of load (Hunter et al., 2002, 2008; Mottram et al., 2005; Bojsen-Møller et al., 2011), number of extremities involved (Kuruganti & Murphy, 2008; Matkowski et al., 2011; Kuruganti et al., 2011), muscle length (Ng et al., 1994; Place et al., 2005; Kooistra et al., 2005; De Ruiter et al., 2005), age (Halin et al., 2003; Hatzikotoulas et al., 2009), gender (Kotzamanidis et al., 2006) and physical fitness level (Pääsuke et al., 1999; Lucia et al., 2000; Usaj, 2001; Halin et al., 2002; Usaj et al., 2007; Cohen et al., 2010). Since hiking endurance is probably highly related to regatta outcome (Blackburn & Hubinger, 1995; Tan et al., 2006; Vangelakoudi et al., 2007), we also summarize the influence of these parameters on endurance time.

It is not surprising that endurance time is inversely related to the exercise intensity during sustained submaximal isometric exercise (Crenshaw et al., 1997; Boyas & Guével, 2011). It has been shown that isometric knee extension contractions at 30% to 40 % MVC show a stronger MPF-decrease than when the same contractions were performed in an ischemic situation. Above 40 % MVC, no differences in MPF-decrease were observed between the non-ischemic and ischemic situation, suggesting that above 40 % MVC intramuscular pressure is sufficiently high to cause ischemia and MPF is very sensitive to changes in intramuscular blood flow (Zwarts & Arendt-Nielsen, 1988). The study of Crenshaw indicated a significantly higher MPF-decrease in 70 % MVC than in 25 % MVC whereas a significantly higher RMS-increase in 25 % MVC compared to 70 % MVC was observed. This indicates that differences exist between MPF and RMS changes for low versus high contraction intensities

(Crenshaw et al., 1997). A popular thought is that MPF-decrease during contraction levels above 45 % MVC is caused by a decrease in the membrane conduction velocity occurring during the fatiguing process due to local metabolic changes and ion shifts in the muscle (Brody et al., 1991). At or below 30 % MVC, when blood flow is likely maintained, MPF decreases are primarily due to neural changes (Zwarts & Arendt-Nielsen, 1988; Löscher et al., 1994), and is referred to as "non-metabolic" (Fuglevand et al., 1993). RMS changes, however, have been constituted as time-dependent recruitment of unfatigued motor units, the recruitment of larger unfatigued motor units and/or grouped firing of motor units (Bigland-Ritchie et al., 1986; Löscher et al., 1994). It has also previously been shown that low-force contractions involve only a fraction of the motor-unit pool and that these are predominantly type I fibers. As exercise progresses, these fibers fatigue and thus require the type II fibers to help generating enough muscle force (Bigland-Ritchie et al., 1986). The fact that both EMG and intramuscular pressure (IMP) demonstrate differences during low versus high contraction levels, suggests that a common factor changes IMP and EMG fatigue indicators (Crenshaw et al., 1997). All the findings above also suggest that there is a close relationship between intrinsic muscle properties and central nervous system recruitment strategies which is entirely different for fatiguing high and low level isometric contractions (Fallentin et al., 1993).

Besides exercise intensity, the type of load will also influence the sEMG amplitude and endurance time. Two load types are distinguished: a force task in which the subject has to maintain a certain contraction force for as long as possible with visual feedback of the force, and a position task in which the subject has to sustain a certain load with visual feedback of the joint angle (Bojsen-Møller et al., 2011). In both dorsiflexor and elbow flexor muscles, the endurance time turned out be lower for the position task than the force task. It was suggested that this difference involved a greater level of neural activity and motor unit recruitment (i.e. RMS-increase) during the position task, but did not involve a difference in co-activation (Hunter et al., 2002, 2008; Mottram et al., 2005). In contrast, the knee extensor muscle shows no significant different endurance time between a position and a force task (Bojsen-Møller et al., 2011). This may partly be attributed to the high joint stability of the knee and the volume of co-contracting muscle, such that the mechanical design of the relevant joint and muscle actuators may influence task dependency during sustained submaximal contractions (Bojsen-Møller et al., 2011).

Also, the number of extremities involved will influence the neural activity and endurance time during sustained submaximal isometric knee extension exercise. Several studies remarked that a longer endurance time was seen in unilateral versus bilateral knee extension exercise (Kuruganti & Murphy, 2008; Matkowski et al., 2011; Kuruganti et al., 2011). Several studies demonstrated a significantly different level of RMS at task failure, suggesting that alterations differ between unilateral or bilateral tasks (Kuruganti & Murphy, 2008; Matkowski et al., 2011). This difference was explained by motor unit recruitment (and thus endurance time) which depends on the muscle mass involved (Hunter et al., 2004). Small muscles have a better muscle perfusion during exercise, as there is only a small intramuscular pressure generated (Williams, 1991; Seals, 1993; Smolander et al., 1998). As a consequence, less recruitment of fresh motor units is required, due to less metabolite accumulation (Brody et al., 1991).

Furthermore, endurance time during sustained submaximal isometric knee extension is also inversely related to muscle length and thus positively related to knee angle (Place et al., 2005; Kooistra et al., 2005). Place & colleagues (2005) suggested that this difference is due to a different excitation-contraction coupling in short compared to longer muscle length sustained isometric contraction at 20 % MVC. In contrast, Kooistra & colleagues (2005) and De Ruiter & co-workers (2005) suggested that differences in endurance during sustained isometric knee extension at different knee angles do not find their origin in differences in central activation and blood flow but may be a consequence of muscle length-related differences in metabolic cost (i.e. oxygen consumption). Also, Ng & colleagues (1994) suggest that at shorter muscle length a lower internal muscle force is created, resulting in a smaller cardiovascular response in comparison to an absolute basis and an enhanced endurance capacity.

Also, age turned out to be an influencing factor for MPF-decrease (Halin et al., 2003). During a 30 s sustained maximal isometric elbow flexion exercise, men displayed a significantly greater MPF-decrease compared to boys (Halin et al., 2003). This difference could be due to a greater accumulation of metabolic and ionic by-products (Tesch et al., 1978; Brody et al.,

1991) induced by a greater participation of type II motor units for men compared to boys (Kupa et al., 1995). The greater participation of type II fibers in men could be due to a higher level of neuromuscular activation and/or to a predominance of type II fibers in their elbow flexor muscles compared with boys (Glenmark et al., 1992). However, the only study in submaximal conditions (i.e. during 10 min sustained isometric plantar flexion at 20 % MVC) demonstrated very similar agonist and antagonist MPF- and RMS-patterns and levels between boys and men (Hatzikotoulas et al., 2009), probably due to the main recruitment of type I fibers at this low submaximal level, thus removing the inherited age related differences in fatigue occurring during maximal muscular actions (Glenmark et al., 1992; Halin et al., 2003). However, previous studies have attributed the faster recovery for children to faster PCr replenishment (Ratel et al., 2008), faster acid base regulation (Kaczor et al., 2005), faster cardio respiratory kinetics (Ratel et al., 2002) and shorter perfusion distances (Falk & Dotan, 2006) compared to adults.

Moreover, the influence of gender to submaximal isometric contraction turned out to differ between adults and children. For children, sEMG patterns during 10 min plantar flexion at 20 % MVC appeared to be similar in boys and girls (i.e. due to similar agonist-antagonist activation) (Kotzamanidis et al., 2006), whereas adults showed higher RMS-increase (and lower endurance time) during sustained isometric elbow flexion at 20 % MVC for men compared to women (Hunter et al., 2004). Research assumed that this was due to a higher muscular mass and a higher type II content in the muscles of men compared to woman (Hunter et al., 2004). Moreover, the study of Clark investigated sEMG patterns during sustained isometric knee extension at 25 % MVC (Clark et al., 2005). The gender difference (woman could sustain longer than men) was related to the activation of the M. rectus femoris. Woman seemed to recruit the knee extensor muscles more synergistically than men, which resulted in a better neuromuscular coordination and maybe to a better blood flow during this exercise (Clark et al., 2005).

Finally, sEMG patterns will be largely dependent on the physical fitness level (endurance trained, strength trained or untrained). During 25 s sustained maximal isometric elbow flexion in strength trained (gymnasts) and untrained children, the gymnasts showed a steeper MPF-decrease than the untrained children (Halin et al., 2002). Since the MPF-decrease was related to the maximal strength (Halin et al., 2002), it was suggested that the difference in MPF-decrease was due to the higher strength capacity inducing the spatial and/or temporal recruitment of the more fatigable fast motor units in gymnasts (Viitasalo & Komi, 1978). The same effect (greater MPF-decrease) was reported during 20 s isometric knee extensions at 30 and 60 % MVC in weightlifters compared to untrained adults (Felici et al., 2001). Those observations seemed to be related to changes in the structure of the muscle (Viitasalo & Komi, 1978) or the pattern of activation (i.e. less RMS-increase) (Felici et al., 2001). As a result of these neuromuscular adaptations to strength training, strength-trained athletes will show longer endurance time during sustained submaximal knee extension exercise compared to untrained men (Pääsuke et al., 1999; Usaj, 2001, 2002). Besides strength training, also endurance training enhances endurance time during sustained isometric knee extension at 50 % MVC (Grandys et al., 2008). It was suggested that endurance training causes on the one hand more type I fibers (Costill et al., 1976; Tesch et al., 1983) and on the other hand a sarcoplasmatic hypertrophy of muscle fibers expressed by increase in the amount of mitochondrial proteins, glycogen, creatine phosphate and myoglobin (Gollnick et al., 1972; Pääsuke et al., 1999). In general, it is suggested that endurance time during sustained submaximal isometric exercise will increase by altering the level (i.e. RMS-increase) and pattern of muscle activation (i.e. more synergistically (Hunter & Enoka, 2003) or more synchronized (Fling et al., 2009) motor unit recruitment) (Hunter & Enoka, 2003).

The past decade, the research group of Boyas, Maïsetti, Guével & colleagues have been focusing on the prediction of endurance in sustained submaximal knee extension exercise, because this could be useful in the sport-related field (e.g. dinghy sailing) minimizing the duration of the endurance capacity test and so reducing the influence of psychological factors as motivation and tolerance to pain (Maïsetti et al., 2002c, 2002b; Boyas & Guével, 2011). They showed that the exercise intensity, and to a lesser degree the joint angle influenced the ability to predict the endurance time. Furthermore, the higher the exercise intensity (75%, 50%, 25% MVC), the higher the correlation between MPF over the first 30 s of the protocol and endurance time ($r = 0.97$ at 75 % MVC; $r = 0.92$ at 50 % MVC; $p < 0.05$ and not significant at 25 % MVC) (Boyas & Guével, 2011). This fact could be related to differences in relative contribution of central and peripheral fatigue that seems to change according to the exercise intensity (Boyas & Guével, 2011). However, in terms of sailing-specific screening or evaluation tool, endurance time prediction based on sEMG parameters was indicated not to be reliable, probably because of the great number of muscles and joints involved in hiking (Boyas et al., 2009).

2.2. Near infrared spectroscopy (NIRS)

NIRS is an objective tool that allows continuous, non-invasive monitoring of tissue oxygenation and hemodynamics to measure microvascular oxygen extraction (Van Beekvelt, 2002; Pereira et al., 2007; Felici et al., 2009; Boone, 2010; Ferrari et al., 2011; Celie et al., 2012). Its functioning is based on the relative transparency of the tissue for near infrared light (at wavelengths of 700 to 1000 nm) and on the principle that the absorption characteristics of hemoglobin (Hb) and myoglobin (Mb) depend on their oxygen (O_2) saturation (Boushel & Piantadosi, 2000).

Near infrared spectroscopy (e.g. Oxiplex TS), consists of 8 light-emitting (i.e. at 750 and 830 nm wavelength) diodes and a light detector, with a distance of 2.0-3.5 cm between the light source and the detector (Boone et al., 2010; Celie et al., 2012). The emitted NIR-light which follows a banana-shaped track through the tissue (figure 13) (Cui et al., 1991), is partially absorbed by several chromophores present in the muscle tissue: cytochrome oxidase, hemoglobin (Hb) and myoglobin (Mb) (Van Beekvelt, 2002). Cytochrome oxidase is the terminal enzyme of the mitochondrial respiratory chain reaction transferring the electrons to molecular oxygen. Because the amount of cytochrome oxidase in the muscle is relatively low compared with Hb and Mb, changes in cytochrome oxidase (i.e. < 5%) are lost within the noise of the signal. Therefore, the contribution of cytochrome oxidase in the in vivo muscle studies can be neglected (Van Beekvelt, 2002). Hemoglobin is the main component of the erythrocytes and the oxygen carrier of the blood. Myoglobin is present within the muscle cell and facilitates intracellular oxygen transport. Both Hb and Mb ([Hb+Mb]) have an oxygen bound (i.e. oxy) and oxygen unbound (i.e. deoxy) form (Van Beekvelt, 2002). The absorption spectra of [Hb+Mb] differ based on the level of O_2 bound. In this way, NIRS can register the (relative change in) oxygenated hemoglobin + myoglobin concentration (oxy[Hb+Mb]) and deoxygenated hemoglobin + myoglobin concentration (deoxy[Hb+Mb]) in the muscle tissue. The absorption spectra of Hb and Mb overlap and are therefore indistinguishable with NIRS (Ferreira et al., 2005; Boone, 2010). Recently, it has been suggested that myoglobin was estimated to contribute for 70 % of the changes in NIRS from rest to peak exercise (Davis & Barstow, 2013).

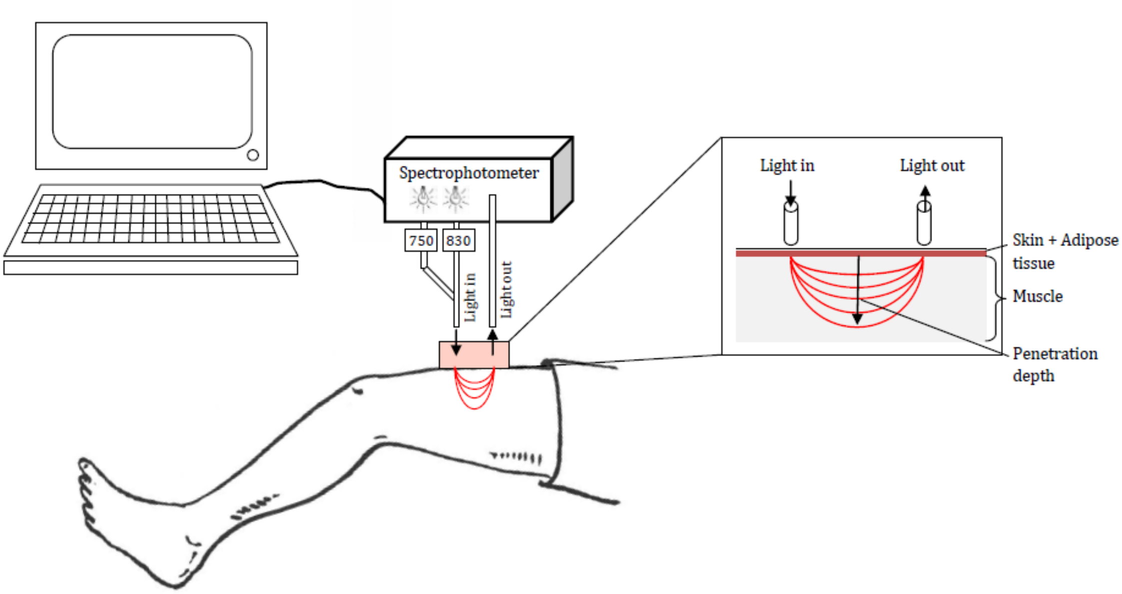


Figure 13: *Schematic presentation of the spectrophotometer set-up emitting light of 3 wavelengths. The light travels through the tissue in a banana shape, the spectral wavelengths of the NIR-light are scattered and detected by the receiver.(based on Van Beekvelt, 2002)*

NIRS records the oxy[Hb+Mb], deoxy[Hb+Mb], total[Hb+Mb] (i.e. the sum of the oxy[Hb+Mb] and deoxy[Hb+Mb]) and saturation (i.e. oxy[Hb+Mb] relative to total[Hb+Mb]) (Van Beekvelt, 2002). Deoxy[Hb+Mb] is a parameter that can provide more insight into the microvascular oxygen uptake kinetics (Grassi et al., 2003; Boone, 2010; Celie et al., 2012). This is based on two assumptions: (1) deoxy[Hb+Mb] is less affected by changes in blood volume under this NIRS-probe compared to oxy[Hb+Mb] (Maehara et al., 1997; Chuang et al., 2002; Grassi et al., 2003) and (2) deoxy[Hb+Mb] reflects the balance between O_2delivery and O_2utilisation and can therefore be considered as an estimation of microvascular O_2 extraction (DeLorey et al., 2003; Grassi et al., 2003). The Fick-principle (i.e. $VO_{2m} = Q_m \times C_{(a-v)}O_2$) can be used to interpret changes in O_2 extraction (as deoxy[Hb+Mb]). In this way, NIRS, and more specifically deoxy[Hb+Mb], can be a useful non-invasive tool to estimate relationship between oxygen supply to oxygen utilization during hiking exercise. The validity of NIRS in exercising human muscle was established by Mancini & colleagues (1994) who reported that NIRS deoxygenation measurements were closely correlated to venous oxygen saturation. The reliability of M. vastus lateralis NIRS registration during incremental maximal cycling exercise was documented to be 0.97-0.98 ($p < 0.05$) (Subudhi et al., 2007). Also, the reproducibility of the oxygenation measurements in the vastus lateralis during the maximum number of knee extensions performed at slow ($r = 0.73$-0.76; $p < 0.05$) and fast ($r = 0.85$-0.97; $p < 0.05$) movement velocities (Pereira et al., 2005) and during isotonic knee extensions ($r = 0.85$; $p < 0.05$) has been documented (Tanimoto & Ishii, 2006).

Also the rate of oxy[Hb+Mb]-increase or deoxy[Hb+Mb]-decrease after cessation of exercise or occlusion is used as an index of reoxygenation (Van Beekvelt, 2002). This variable reflects the initial inflow of oxy[Hb+Mb] over a fixed time period. Thus, this reoxygenation rate is thought to reflect the fast initial recovery rate at which primarily vascular components are restored (Van Beekvelt, 2002). Vogiatzis & colleagues (2008) measured the half time reoxygenation index (i.e. the time to accomplish 50 % of the post-exercise peak oxygenation) in sailors.

According to current literature, NIRS responses during sustained submaximal isometric contraction are dependent on several aspects: the muscles registered (Azuma et al., 2000), the contraction intensity (Vøllestad et al., 1990; Crenshaw et al., 1997; Griffin et al., 2001; Kalliokoski et al., 2003; De Ruiter et al., 2007), the number of extremities involved (Richardson et al., 1995; Ogata et al., 2002), the muscle length (Rundell et al., 1997; Hisaeda et al., 2001; Szmedra et al., 2001; De Ruiter et al., 2005), age (Moalla et al., 2006), gender (Clark et al., 2005), physical fitness level (Chance et al., 1992; Bae et al., 1996; Pääsuke et al., 1999; Lucia et al., 2000; Usaj, 2002, 2001; Aagaard et al., 2001; Costes et al., 2001; Ding et al., 2001; Neary et al., 2002; De Ruiter et al., 2007; Usaj et al., 2007) and the adipose tissue (Van Beekvelt et al., 2001a, 2002). Each of these aspects is elaborated in following paragraphs.

NIRS responses differ depending on the muscles registered. The study of Azuma & colleagues (2000) showed that during sustained knee extension exercise at 30 % MVC, oxygen saturation decreased to a lower level in the M. vastus lateralis (saturation difference = -10.3 ± 1.7 %) than in the M. rectus femoris (-4.0 ± 1.0 %).

NIRS parameters in the M. vastus lateralis (but not in the M. rectus femoris) are dependent on the contraction intensity (Azuma et al., 2000). During low isometric contraction intensity exercise (e.g. at 10 % MVC), blood flow and muscular oxygen extraction will increase (Kalliokoski et al., 2003). But with increasing muscle load and thus increasing intramuscular pressure, blood flow will slightly decrease and muscular oxygen extraction will continue to increase. Spurway (2007) investigated the changes in blood flow with Doppler measurement on an isometric leg-extension ergometer. He reported that at 25 to 30 % MVC the blood flow is restricted, but not yet totally occluded. VØllestad & colleagues (1990) investigated repeated isometric contractions from the M. quadriceps at 30 % MVC, sustained until exhaustion. They reported that the increase in oxygen consumption resulted from a 54 % increase in blood flow and 34 % higher oxygen extraction. The higher blood flow was probably due to both increased skin circulation and higher perfusion in muscle regions with low intramuscular pressures. These results suggested that despite the high intramuscular pressure in some parts of the M. quadriceps, blood flow is not totally restricted during repeated isometric contractions at 30 % MVC, sustained until exhaustion. However, De Ruiter & colleagues (2007) reported a M. vastus lateralis and medialis blood flow occlusion at 25 % maximal torque capacity (MTC) and a M. rectus femoris blood flow occlusion at 35 % MTC, during isometric contraction. The M. rectus femoris is most likely occluded at a higher contraction intensity because this biarticular muscle is in general less activated during submaximal isometric knee extension, compared to the monoarticular M. vastus lateralis and medialis (De Ruiter et al., 2005). These % MTC of total muscle occlusion are quite low. However, although the intramuscular pressure in the M. quadriceps is quite low at the onset of a fatiguing isometric contraction at 25 % MVC (Crenshaw et al., 1997), Griffin & co-workers (2001) suggests that the intramuscular pressure increases over the course of sustained contraction which means that at the end the intramuscular pressure is the same as the pressure exerted by a 70 % MVC. Moreover, knowing that intramuscular pressure is higher in deep parts than in superficial parts of the muscle (Sadamoto et al., 1983; Sejersted et al., 1984), it is suggested that when superficial occlusion is suggested from NIRS registration, the blood flow in the muscle will certainly be occluded.

Several studies indicated that NIRS-responses are also dependent on the number of extremities involved. Richardson & colleagues (1995) and Ogata & co-workers (2002) examined the circulatory responses to two-legged knee extension when arm cranking was added. Although a decrease in blood flow to the leg was seen in the inactive vastus lateralis during arm cranking, there was no significant decrease in blood flow to the leg when the muscle was exercising during arm cranking (Richardson et al., 1995). This suggests that differences in the circulatory responses to leg exercise are related to the muscle mass engaged in the exercise (Richardson et al., 1995; Ogata et al., 2002). According to these data, it should be argued that the quasi-isometric knee extension exercise during hiking should be considered together with dynamic upper body and arm pulling exercise in order to get an integrated view on the NIRS responses during hiking.

Furthermore, several studies showed that muscular oxygen uptake, registered by NIRS, is lower (and thus endurance time is higher) during submaximal isometric knee extension with a knee angle of 30° compared to a knee-angle of 60° or 90° (extended knee = 0°) or in an extended versus flexed knee joint (even when local circulation was controlled) (Hisaeda et al., 2001; De Ruiter et al., 2005). This is reported during maximal as well as during submaximal knee extension. Transferring this to sport-specific research, Rundell & co-workers (1997) reported a 59 % greater change in muscle deoxygenation in the M. quadriceps of speed skaters in the low skating position, indicating that muscle deoxygenation is related to knee and hip joint angle. Moreover, the study of Szmedra & colleagues (2001) in Alpine skiing even suggested that in some skiing positions intramuscular pressure exceeded perfusion pressure which limited blood flow to exercising muscle, known as the “reduce blood flow hypothesis”. These studies all indicate the dependence of muscle length (or joint angle) for the NIR response (Rundell et al., 1997; Szmedra et al., 2001).

To our knowledge, the study of Moalla & colleagues (2006) is the only one which investigated NIR responses during submaximal isometric knee extension exercise by children. This study indicated that the maximal deoxygenation occurred at 50 % of the total endurance time and fell by 76.9 % from the resting value. Similarly, minimal blood volume was observed at 50 % of total endurance time at reached a plateau that lasted until the end of exercise. Also, the significant correlations between muscle oxygenation, blood volume, root mean square amplitude and mean power frequency which ranged from 0.72 to 0.99 (p

< 0.05) suggested that the fatigue resulting from sustained isometric exercise is related to a decrease in oxygenation and blood volume (Moalla et al., 2006).

The study of Clark & colleagues (2005) investigated gender differences during sustained isometric knee extension. The data showed endurance time to failure for females was higher in the non-occluded condition, whereas it was similar for females and males in the occluded condition (Clark et al., 2005). These results suggest that females create a different capacity from males concerning blood flow which makes it possible for them to sustain this isometric knee extension longer. However, the question rises whether the sex difference is only due to muscle blood flow or rather to muscle metabolism or muscle activation pattern (Clark et al., 2005).

Several studies with NIRS have already indicated that an athletic group has a greater capacity for oxygen supply to the working muscles (Chance et al., 1992; Bae et al., 1996; Ding et al., 2001). Therefore, it is suggested that physical fitness level alters the muscle perfusion to muscle oxygen extraction relationship. Moreover, NIRS also indicates faster reoxygenation-kinetics after a certain training period (Costes et al., 2001; Neary et al., 2002). In terms of strength training effect, De Ruiter (2007) showed that the relative torque at which reoxygenation stopped tended to be negatively ($r = -0.49$; $p = 0.07$) related to the maximal strength capacity of the M. vastus lateralis. Thus, a sailor with a higher maximal strength capacity will show a similar relative torque (i.e. % MVC) or a higher absolute torque at which arterial occlusion or oxygen supply deficit emerges. However, in contrast to these former theory's, Aagaard & co-workers (2001) showed that with increasing strength, also the pennation angle of the muscle increases. Moreover, the greater the pennation angle of the muscle, the higher the intramuscular pressure in the muscle (Reeves et al., 2004), which suggests that total muscle occlusion possibly exhibit at more or less the same absolute muscle torque. In terms of endurance training effect, Usaj (2001, 2002, 2007) investigated the effect of endurance training in rock climbers. In a first study, Usaj (2002) compared performance on a 30 % MVC sustained handgrip test to exhaustion. Not surprisingly, the rock climbers showed a significantly higher endurance time, probably due to the higher oxy[Hb+Mb] seen in rock climbers compared to controls. Since the tot[Hb+Mb] did not differentiate the two groups, it was suggested that blood volume did not strongly influenced contraction time (Usaj, 2002). In a second study, he compared the performance and NIRS differences to the same handgrip test before and after a 4 week training period, showing that rock climbers demonstrated higher endurance time after training period (Usaj, 2001). Since the difference between the duration of muscle contraction significantly correlated with relative oxygen saturation ($r = -0.88$; $p < 0.05$) and with relative concentration of deoxygenated hemoglobin ($r = 0.87$; $p < 0.05$), it was suggested that the increase in duration is probably dependent on larger muscle deoxygenation as a training effect (Usaj, 2001). However, it should be argued that oxygenation may pass a certain limit where it becomes an important factor of endurance performance during isometric exercise (Usaj et al., 2007).

Importantly, NIRS recordings are highly dependent on the thickness of the adipose tissue (Van Beekvelt et al., 2001a). The study of Van Beekvelt & colleagues (2001a) indicated that muscular VO_2 measured by NIRS was underestimated when the adipose tissue thickness increased, whereas the study of Yamamoto & co-workers (1996) showed a 50 % decrease in absorbance when the thickness of the fat layer increased from 5 to 10 mm and a 25 % decrease when fat layer increased from 2.5 to 5 mm. These data suggest that the sensitivity decreases with increasing adipose tissue thickness (Yamamoto et al., 1996; Van Beekvelt et al., 2001a). Therefore, it is suggested to interpret NIRS registration not as absolute variables, but as relative values expressed relative to the occlusion amplitude measured during arterial occlusion (Van Beekvelt, 2002). Arterial occlusion is conducted by inflating a cuff to 260 mmHg which results in a blockage of both the venous outflow and arterial inflow (Van Beekvelt, 2002). Lacking the supply of well oxygenated blood, muscle metabolism fully depends on the available oxygen in local capillaries and muscle cells. Depletion of local available oxygen stores during arterial occlusion is monitored by NIRS as a decrease in oxy[Hb+Mb] or a concurrent increase in deoxy[Hb+Mb] (Van Beekvelt et al., 2001a). When oxy[Hb+Mb]-decrease & deoxy[Hb+Mb]-increase stagnates, the amplitude is determined as the difference between resting value and maximal value (Celie et al., 2012).

Yamada & colleagues (2003) found a positive correlation between integrated EMG and muscle oxygenation level during 10 seconds sustained isometric contraction at 30 %, 50 % and 70 % MVC. In a following study, they reported that changes in oxyHb and deoxyHb indicate muscle fatigue assessed by EMG (Yamada et al., 2008). This was confirmed by the study of Moalla & colleagues (2006) where changes in EMG (MPF and RMS) were also associated with changes in NIRS variables (quadriceps muscle oxygenation, blood volume).

This suggested that fatigue resulting from sustained isometric knee extension exercise is related to a decrease in oxygenation and blood volume (Moalla et al., 2006). It could therefore be very interesting to investigate this in a sailing-specific quasi-isometric situation.

Although NIRS is a frequently used method to observe tissue oxygenation and hemodynamics, several limitations of this research method should be mentioned. Firstly, not all studies support the use of NIRS in its application as a non-invasive technique for muscle metabolism or hemodynamics (Hicks et al., 1999; McDonald et al., 1999). Since Van Beekvelt & co-workers (2001b) showed that there are differences between local muscle oxygen uptake data using NIRS, this discrepancy between the NIRS and femoral results reported by McDonald & co-workers (1999) and Hicks & colleagues (1999) is likely related to the area of sampling of the NIRS probe (localized to the small vessels) versus the regional venous return from the entire leg musculature (obtained from direct venous blood sampling) (Neary, 2004). In line with this, Crenshaw & colleagues (2010) showed that regional differences in oxygenation (proximal versus distal) are not associated with differences in muscle activation or fatigue development. Secondly, tot[Hb+Mb] is no valid representation of muscle perfusion during dynamic exercise (Van Beekvelt, 2002). Therefore, NIRS is probably not appropriate to reflect muscle perfusion.

3. Gaps in current literature

Sailing is a widely known and practiced Olympic water sport. Over the years, the physical requirements of competitive dinghy sailors have become of increased importance. However, to date there is no clarity on the physical and physiological characteristics that determine dinghy sailing performance and is even unexplored terrain for youth sailors who serve as pool for the next generation of elite athletes. This kind of information is of great importance in order to optimize the development of young athlete's physical capacity and progression up to elite adult sailor.

The last 20 years, several research groups have undertaken great efforts in adding knowledge to this sport-specific research area, focusing mainly on the cardiorespiratory, -vascular and metabolic demands of hiking (table 15). One research group (Maïsetti et al., 2006; Boyas et al., 2009) took the effort to explore electromyography during sustained submaximal isometric knee extension exercise to exhaustion as a representation of hiking exercise. Another research group (Vogiatzis et al., 2008, 2011) conducted near infrared spectroscopy registrations during simulated hiking exercise. However, to date there is no study which provides an integrated view on the physiological mechanisms during upwind sailing exercise. As well, there is still no consensus on the muscular mechanisms which elucidate why *"hiking is hard"* (Spurway, 2007).

Although worldwide, more than 130.000 children are sailing the Optimist, literature review (table 15) points out that scientific literature lacks information on the physiology of Optimist sailing. Only one study investigated the cardiorespiratory responses during Optimist sailing on the water and the cardiovascular responses during sailing on an ergometer (Sailing fitness, Harken, Italy) (Rodio et al., 1999). Additionally, studies investigating EMG and NIRS responses in a pediatric population are scarce (Moalla et al., 2006).

To our knowledge, several types of sailing ergometers have been developed: on the one hand, a type of sailing ergometer which aims to evaluate sailing technique and tactics (Walls et al., 1998; Mulder & Verlinden, 2013), and on the other hand, a type of sailing ergometer which aims to represent the physiological responses during on-water (upwind) sailing or hiking (table 16). However, as indicated in table 15, most of these ergometer use a static ergometer, a static exercise protocol and some of them measure hiking strap load as a representation of the uprighting moment created by the sailor. This implies that these ergometers not truly reflect the physiological responses during on-water hiking. Moreover, none of these ergometers were able to impose a certain quasi-isometric hiking intensity onto the sailor.

Table 15: *Overview of the studies on the indicators of sailing performance, the cardiorespiratory, cardiovascular & metabolic responses during hiking, the muscular responses during hiking and the sailing ergometers in literature.*

	Optimist sailors		Laser sailors	
	Studies	Measurements	Studies	Measurements
Determinants of sailing performance			Blackburn & Hubinger, 1995	Bucket test, sheeting power, handgrip S, max KE S, aerobic fitness, weight
			Tan et al., 2006	hiking moment over 180 s, weight
			Vangelakoudi et al., 2007	45 % MVC KE SE test on a hiking ergometer
			Aagaard et al., 1998	max knee & trunk extensor strength
Cardiorespiratory, cardiovascular & metabolic responses during hiking	***On-water study:*** Rodio et al., 1999		***On-water studies:*** Gallozzi et al., 1993 Vogiatzis et al., 1995 De Vito et al., 1996 Cunningham, 1996 Castagna et al., 2004 Castagna & Brisswalter, 2007	
	Simulation study: Rodio et al., 1999		***Simulation studies:*** Vogiatzis et al., 1993, 1996 Blackburn, 1994 Cunningham et al., 1998 Felici et al., 1999 Cunningham & Hale, 2007 Vangelakoudi et al., 2007	
Muscular responses during hiking			Maïsetti et al., 2006; Boyas et al., 2009	Electromyography (EMG)
			Vogiatzis et al., 2008, 2011	Near infrared spectroscopy (NIRS)
Hiking ergometers	Rodio et al., 1999		Blackburn, 1994	static ergometer, measuring RM and HSL
			Felici et al., 1999	static ergometer, measuring RM
			Vogiatzis et al., 1996, 2008, 2011	static ergometer, measuring HSL
			Cunningham & Hale, 2007	quasi-static ergometer, measuring RM
			Maïsetti et al., 2006; Boyas et al., 2009	static ergometer, measuring RM

Note: HSL = hiking strap load, RM = uprighting moment, S = strength, KE = knee extensor, SE = strength endurance.

4. Research objectives and outline of the dissertation

As illustrated previously, the state of the art concerning dinghy sailing performance demonstrates several gaps and uncertainties. The present dissertation attempts to move sailing literature forward by pursuing three aims, that is: (1) investigating the determinants of dinghy sailing performance, (2) developing a sailing ergometer which accurately represents the physiological responses during on-water upwind sailing, and (3) exploring the physiological mechanisms during submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing) with a distinct focus on the muscle level. By pursuing these three aims, we attempt to establish an integrated view on dinghy sailing performance.

AIM 1: Determinants of dinghy sailing performance

Sailing becomes more and more popular in our country, which is also mirrored in the non-elite sailor population, where many enthusiasts spend a major part of their leisure time on the water and many youngsters perform remarkably well in youth international regatta and tournaments. In this context, **study 1** aimed to identify the determinants of sailing performance for both Optimist and Laser sailors by conducting field tests to elite and non-elite sailors. Further, also a laboratory study was conducted to add more argumentation to the identification of the determinants of dinghy sailing performance for Laser sailors (**study 5**).

AIM 2: Innovation in sailing ergometers

The ultimate objective is to conduct EMG and NIRS registration during upwind sailing exercise. Hence, the second and obvious aim was to develop an upwind sailing ergometer. Three versions of ergometers were developed to support this physiological research. Firstly, a standardized submaximal isometric knee extension protocol on the Biodex was used as a representation of the knee extension exercise during upwind sailing (**study 2**). Secondly, a first attempt was made to develop an Optimist upwind sailing ergometer (**study 3**). However, since the researcher was not in control of the hiking intensity performed by the sailors during protocol, a third version was developed and biologically validated (**study 4 & 5**). This upwind sailing emulation ergometer offers an innovative contribution to this physiological research and to the research area of sailing ergometers.

AIM 3: Mechanisms of submaximal (quasi-)isometric knee extension exercise

The final research aim involves examining both the cardiorespiratory, cardiovascular, metabolic and muscular mechanisms of both Optimist (**study 2 & 3**) and Laser upwind sailing exercise (**study 4 & 5**). Until now, the majority of the work has been focussing on the cardiorespiratory, cardiovascular and metabolic responses. Therefore, we focus on the mechanisms at the muscle level, but within a broad context by combining cardiorespiratory, cardiovascular, metabolic and muscular registrations. At the muscle level, electromyography (EMG) and Near Infrared Spectroscopy (NIRS) are combined to describe the muscle activity and hemodynamics respectively in the M. vastus lateralis during submaximal (quasi-)isometric knee extension exercise as a part of upwind sailing exercise.

To achieve these goals, five studies with each their own purpose and design (described in detail in the second part of this thesis) have been conducted (figure 14). Study 1, 2, 3 and 4 were submitted, reviewed and published in international peer-reviewed journals. Study 5 was submitted and is currently being reviewed.

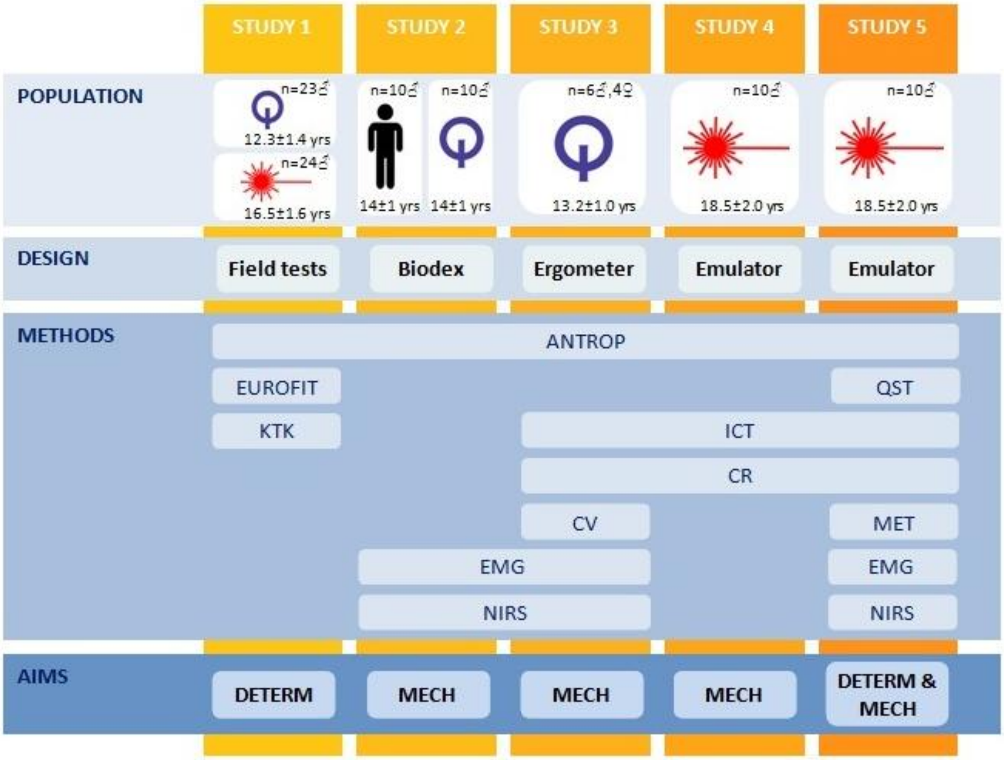


Figure 14: *Overview of the population, study design, methods and aims of the 5 studies conducted in the original research. (Ϙ = Optimist sailors, ӿ- = Laser sailors, Black pictogram = sedentary people, ANTROP = anthropometry, KTK = KörperKoordinationstest für Kinder, QST = quadriceps strength test, ICT = incremental cycling test, CR = cardiorespiratory measurements, CV = cardiovascular measurements, MET = metabolic measurements, EMG = electromyography, NIRS = near infrared spectroscopy, DETERM = determinants, MECH = mechanisms)*

The general discussion (part 3) provides a critical overview of the findings presented in part 2 and attempts to assemble our observations into a model that clarifies the mechanisms related to the determinants of dingy sailing performance. At the bottom, our research theory is converted into practice by sketching the implications for follow-up and training programs, and for future research.

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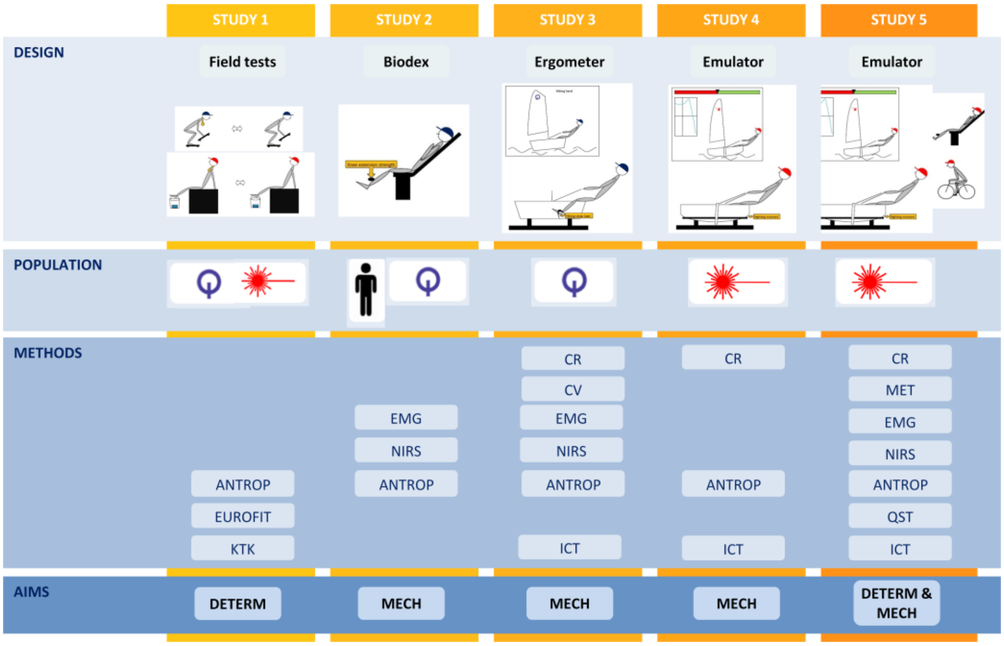
PART 2:

ORIGINAL RESEARCH



	STUDY 1	STUDY 2	STUDY 3	STUDY 4	STUDY 5
DESIGN	Field tests	Biodex	Ergometer	Emulator	Emulator
POPULATION	⚲ ✷	🧍 ⚲	⚲	✷	✷
METHODS	ANTROP EUROFIT KTK	EMG NIRS ANTROP	CR CV EMG NIRS ANTROP ICT	CR ANTROP ICT	CR MET EMG NIRS ANTROP QST ICT
AIMS	DETERM	MECH	MECH	MECH	DETERM & MECH

Study 1:

INDICATORS OF SAILING PERFORMANCE IN YOUTH DINGHY SAILING

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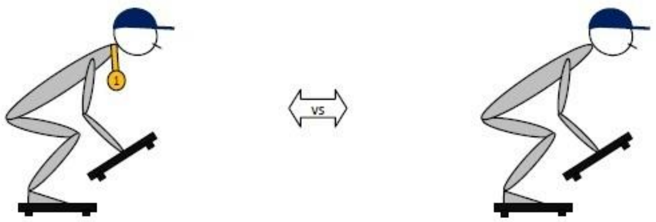

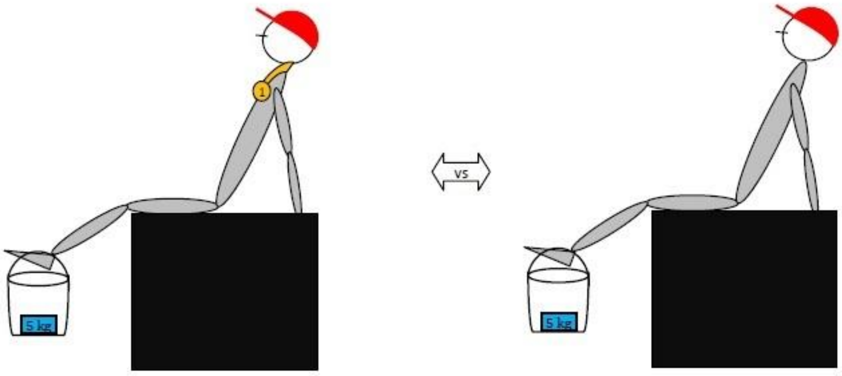

Abstract

This study aimed to determine indicators of sailing performance in 2 (age) groups of youth sailors by investigating the anthropometric, physical and motor coordination differences and factors discriminating between elite and non-elite male optimist sailors and young dynamic hikers. Anthropometric measurements from 23 optimist sailors (mean ± SD age = 12.3 ± 1.4 yrs) and 24 dynamic youth hikers (i.e. Laser 4.7, Laser radial and Europe sailors <18 yrs who have to sail the boat in a very dynamic manner, due to a high sailor to yacht weight ratio) (mean ± SD age = 16.5 ± 1.6 yrs) were conducted. They performed a physical fitness test battery (EUROFIT), motor coordination test battery (Körperkoordinationstest für Kinder) and the Bucket test. Both groups of sailors were divided into 2 subgroups (i.e. elites and non-elites) based on sailing expertise. The significant differences, taking biological maturation into account, and factors discriminating between elite and non-elite optimist sailors and dynamic hikers were explored by means of (M)ANCOVA and discriminant analysis respectively. The main results indicated that 100.0 % of elite optimist sailors and 88.9 % of elite dynamic hikers could be correctly classified by means of two motor coordination tests (i.e. side step and side jump) and Bucket test respectively. As such, strength- and speed-oriented motor coordination and isometric knee extension strength endurance can be identified as indicators of sailing performance in young optimist and dynamic youth sailors respectively. Therefore, we emphasise the importance of motor coordination skill training in optimist sailors (<15 yrs) and maximum strength training later on (>15 yrs) in order to increase their isometric knee extension strength endurance.

Introduction

Dinghy sailing is a multifaceted sport where numerous factors such as morphology, physical fitness and well-developed technical and tactical skills determine performance (Bojsen-Møller et al., 2007). Since the primary actions for dinghy sailing include steering, hiking (i.e. leaning back over the side of the boat) and sheeting (i.e. pulling on the ropes controlling the sails), fitness requirements will vary between boat classes. Tan & colleagues (2006) showed that in elite Olympic Laser sailing, body mass and maximum quadriceps strength are closely related to successful performance. However, no studies have investigated the anthropometric and physical characteristics related to performance in youth sailors in order to get more insight into the physical profile of young sailors and to improve training guidelines in youth sailing.

In Flemish youth sailing (i.e. 8 to 18 years old), two types of one-handed dinghy sailors can be distinguished: the (1) Optimist sailors and the (2) Laser 4.7, Laser radial and Europe class sailors. Young sailors (both boys and girls <15 yrs) compete in the Optimist class up to the age of 15, including the year in which they have their 15th birthday (IODA-Basics, 2010). Once outgrown the Optimist dinghy, there is a large choice of boat types, depending on the sailors morphology and personal interest or preference. However, in Flanders, one-man-dinghy sailors choose very often the Laser 4.7, subsequently followed by the Laser radial or the Europe class. The term 'dynamic hikers' for the Laser and Europe sailors was introduced by Bojsen-Møller and co-workers (2007) who presented a classification system for Olympic sailors based on their main body position during sailing in order to enable sailor-specific training recommendations. As such, they identified two types of side-deck hikers (i.e. helmsmen and single-handed dinghy sailors): 'static hikers' who, as a result of the yacht design and its relatively large displacement (high yacht to sailors weight ratio), are characterized by rather static hiking as opposed to the 'dynamic hikers' who, due to a high sailor to yacht weight ratio, are required to sail the boat in a very dynamic manner (Felici et al., 1999; Bojsen-Møller et al., 2007). It is suggested that dynamic hikers must endure prolonged isometric activation of knee extensors and hip flexors while other factors such as body adjustments and yacht displacement add an aerobic dimension to this sailing exercise (Bojsen-Møller et al., 2007; Cunningham & Hale, 2007; Spurway et al., 2007; Vangelakoudi et al., 2007).

It is important to understand that the development of an elite sailor is a continuous growth process with several phases of sportsmanship. In order to understand and evaluate the sailors' evolution from novice to high level elite sailor, several validated test batteries could be used to examine indicators of sailing performance throughout different stages of youth sailing (e.g. optimist sailing or later on). In order to get more insight into the characteristics of youth sailors and to improve the training guidelines and field evaluation tests for youth sailors, this study aimed to determine indicators of sailing performance in 2 (age) groups of youth sailors. This was done by investigating the anthropometric, physical and motor coordination differences and factors discriminating between elite and non-elite male optimist sailors and young dynamic hikers.

Methods

Sample and study design

Forty seven male youth sailors (aged 10-18 years) participated in this study. The sample was divided into two groups of youth sailors, i.e. optimist sailors (n = 23, mean ± SD age = 12.3 ± 1.4 yrs with a range from 10 to 15 yrs) and dynamic hikers, which includes Laser 4.7, Laser radial and Europe sailors (n = 24, mean ± SD age = 16.5 ± 1.6 yrs with a range from 14 to 18 yrs), and two sailing levels (elite and non-elite) based on their expertise. The youth sailors who were selected for the Flemish national team (based on the observations and opinion of the national youth coaches) were assigned to the elite group. These assignments result in the following sub-groups: elite optimist sailors (n = 7), non-elite optimist sailors (n = 16), elite dynamic hikers (n = 9) and non-elite dynamic hikers (n = 15). The study received approval from the Human Ethics Committee of Ghent University Hospital. Informed parental consent was obtained. The subjects were instructed to perform no strenuous exercise 48 h before their visit to the lab. In total, the visit to the lab, organized as a rotation system, took 3 hours and started by filling in their training history. Then, anthropometric assessments were conducted followed by a standardized 10min warming-up and evaluation of the gross motor coordination by the Körperkoordinationstest für Kinder (KTK) (Kiphard & Schilling, 2007). Further, Overall physical fitness was evaluated by the EUROFIT test battery (Council of Europe, 1988). About 4 min of recovery was allowed between the different tests and at least 20 min of recovery was allowed before the Bucket test (Tan et al., 2006) and at least 20 min of recovery before the 20m endurance shuttle run were performed. Since the test session was organized as rotation system, every examiner (from 6 trained examiners of the Department Movement & Sports Sciences) always carried out the same measurement.

Training history

Sailing experience (years) and sailing practice hours per week (hours on the water) were questioned. In younger sailors, the parents helped to answer these questions.

Anthropometry

The following anthropometric measurements were assessed according to standardized protocols (Lohman et al., 1988): Height and sitting height (to the nearest 0.1 cm; anthropometer GPM, DKSH Switzerland), body mass (0.1kg; Electronic SECA, 815 Elegantia) and 10 skinfold thicknesses (Harpenden skinfold caliper) (Parizková, 1961). Body fat percentage (0.1 %) was calculated according to the method of Parizková (Parizková, 1961). To estimate the maturation status of the sailors, a biological maturation index was calculated using equation from Mirwald & colleagues (2002): maturity offset = -9.236 + 0.0002708 (leg length x sitting height) – 0.001663 (age x leg length) + 0.007216 (age x sitting height) + 0.02292 (weight/height). This technique, based on anthropometric variables, predicts maturity offset (MO) as a measure of years from peak height velocity.

Gross motor coordination (KTK)

Gross motor coordination was evaluated by the Körperkoordinationstest für Kinder (KTK) (Kiphard & Schilling, 2007). This test battery is a reliable and valid instrument for use in children between 5 and 15 years as recently tested for suitability in the Flemish population (Vandorpe et al., 2011a). The following KTK subtests were performed (all barefooted):

(1) Walking backwards (WB) three times along each of three balance beams (3 m length; 6, 4.5 and 3 cm width, respectively; 5 cm height). A maximum of 24 steps (eight per trial) were counted for each balance beam, which comprises a maximum of 72 steps (24 x 3 beams) for this test (Kiphard & Schilling, 2007; Vandorpe et al., 2011a). The number of steps were counted and summed over the 9 travels.

(2) Side step (SS): Moving across the floor in 20 s by stepping from one plate (25 cm x 25 cm x 5.7 cm) to the next, transferring the first plate, stepping on it, etc. The number of

relocations was counted and summed over two trials (Kiphard & Schilling, 2007; Vandorpe et al., 2011a).

(3) Side jump (SJ): Jumping laterally as many times as possible over a wooden slat (60 cm x 20 cm x 5 cm each) in 15 s. The number of jumps over two trials was summed (Kiphard & Schilling, 2007; Vandorpe et al., 2011a).

Physical fitness (EUROFIT)

The EUROFIT test battery (Council of Europe, 1988) was used to assess physical fitness. All tests were performed in bare feet (except the endurance shuttle run) following EUROFIT guidelines which are extensively described in the Council of Europe (1988).

Hiking endurance with incremental resistance (Bucket test)

This is a maximal incremental test of hiking endurance based on the protocol established by Blackburn and Tan (Blackburn, 2000; Tan et al., 2006). However, since we conducted this test to a pediatric population, starting load of the Bucket test was reduced from 15 kg to 0 kg. The subjects had to maintain a knee angle of > 130° (the angle between the tibia and the bench) as 5 kg was added every minute until the subject could no longer hold it at the prescribed angle. The subjects braced themselves by gripping the bench and were allowed to shift the load from one leg to another. Verbal encouragement was provided throughout the duration of the tests. The subjects' final endurance time was recorded to the nearest second.

Statistical analysis

Data were analyzed using SPSS version 15.0 (SPSS inc., Chicago IL, USA). Multivariate analysis of covariance (MANCOVA) was used to identify the significant differences in the anthropometric, physical fitness, and motor coordination parameters between elite and non-elite optimist sailors and dynamic hikers (Matthys et al., 2011). For the sailing-specific Bucket test, an univariate analysis of covariance (ANCOVA) was used for the same purpose. Age and maturity offset (MO) were used as covariates to account for the significant age and maturity differences, detected by using an independent sample T-test. Furthermore, for each group of youth sailors, a stepwise discriminant analysis with sailing level as the grouping variable and the significantly different anthropometric, physical fitness, and motor coordination variables as the independent variables, was conducted to identify the most discriminating variables in classifying youth sailors by their sailing expertise level. The discriminating variables with their respective Wilks' lambdas and p-value, canonical discriminant function coefficients (which determine the discriminating model), canonical correlation (r_c) and classification percentages were denoted (Vandorpe et al., 2011b). Significance level was set at $p < 0.05$.

Results

Elite optimist sailors were significantly older (13.6 ± 1.2 versus 11.7 ± 1.1 yrs) (p = 0.002, t = 3.537) and more mature (2.2 ± 1.0 versus 0.7 ± 0.8 years before age at peak height velocity) (p = 0.002, t = 3.462) than the non-elite optimist sailors. Equally, also the elite dynamic hikers were significantly older (17.5 ± 1.0 versus 15.9 ± 1.4 yrs) (p = 0.008, t = 2.903) and more mature (3.0 ± 0.9 versus 1.7 ± 1.1 years after age at peak height velocity) (p = 0.006, t = 3.024) than the non-elite dynamic hikers. Therefore, age and maturity offset (MO) were taken into account as covariates in the (M)ANCOVAs.

Results from the (M)ANCOVAs are presented in table 1. It was indicated that in all groups of youth sailors, elites sailed significantly more (hours per week) (p = 0.050 and p = 0.027). However, experience (number of years) did not differ significantly between elites and non-elites. Furthermore, for all groups of youth sailors, there were no significant differences between elites and non-elites in anthropometric variables. In the optimist group, there was no significant difference between elites and non-elites in physical fitness (EUROFIT measures). However, in the dynamic hikers group, a significant better score for the elite dynamic hikers was demonstrated on the 5m (p = 0.039) and the 20m shuttle run (p = 0.030) as compared to the non-elite dynamic hikers. In addition, elite optimist sailors show a significant better score on the KTK side step (p = 0.008) and side jump test (p = 0.017), compared to the non-elite optimist sailors. However, in the dynamic hikers group, no significant difference was demonstrated. As last, the sailing-specific Bucket test demonstrated that both elite dynamic hikers and elite optimist sailors show a significantly higher knee extension strength endurance time than non-elite dynamic hikers and non-elite optimist sailors (p = 0.050 and p = 0.002).

Table 1: *Significant differences in training history, anthropometry, physical fitness (EUROFIT), motor coordination (KTK) and sailing-specific Bucket test between elite and non-elite optimist sailors and dynamic hikers.*

Profile group	**Mean ± SD**		**(M)ANCOVA**		**Covariates**	
	Non-elite	**Elite**	**p**	**F**	**Age**	**Mat Offset**
TRAINING HISTORY						
Optimist sailors *	**(n=8)**	**(n=6)**	**0.050**	**2.309**	**n.s.**	**n.s.**
Experience (years)	3.6 ± 1.8	4.3 ± 1.4	n.s.			
Practice (hours/week) *	5.3 ± 1.9	9.8 ± 2.2	0.050	4.820	n.s.	n.s.
Dynamic hikers *	**(n=10)**	**(n=9)**	**0.024**	**4.928**	**n.s.**	*****
Experience (years)	6.1 ± 2.3	8.6 ± 2.1	n.s.			
Practice (hours/week) *	5.8 ± 3.4	11.6 ± 4.1	0.027	6.014	n.s.	n.s.
ANTHROPOMETRY						
Optimist sailors	**(n=16)**	**(n=7)**	**n.s.**			
Height (cm)	146.5 ± 10.9	157.1 ± 8.7				
Weight (kg)	37.6 ± 7.3	46.4 ± 7.4				
Fat percentage (%)	16.3 ± 3.8	13.3 ± 2.5				
Sitting Height (cm)	75.4 ± 5.1	80.8 ± 3.4				
Dynamic hikers	**(n=15)**	**(n=9)**	**n.s.**			
Height (cm)	176.6 ± 7.4	176.3 ± 4.8				
Weight (kg)	64.9 ± 8.4	72.0 ± 5.5				
Fat percentage (%)	14.1 ± 3.4	14.1 ± 1.8				
Sitting Height (cm)	90.4 ± 4.5	92.1 ± 2.4				
PHYSICAL FITNESS (EUROFIT)						
Optimist sailors	**(n=16)**	**(n=7)**	**n.s.**			
Flamingo balance (n)	11.9 ± 4.8	7.1 ± 3.6				
Plate tapping (n)	14.0 ± 2.9	12.2 ± 1.0				
Sit and reach (cm)	19.9 ± 5.4	28.1 ± 3.0				
Standing broad jump (cm)	157.5 ± 22.5	175.7 ± 13.4				
Handgrip (kg)	25.5 ± 8.1	31.4 ± 4.0				
Sit-up (n)	28.4 ± 5.0	31.9 ± 3.8				
Bent arm hang (s)	15.1 ± 13.1	27.9 ± 16.9				
Shuttle run 5m (s)	21.9 ± 1.4	20.6 ± 0.8				
Shuttle run 20m (min)	7.3 ± 1.2	8.1 ± 0.8				
Dynamic hikers *	**(n=15)**	**(n=9)**	**0.050**	**1.530**	*****	*****
Flamingo balance (n)	9.9 ± 3.9	7.9 ± 5.2	n.s.			
Plate tapping (n)	10.1 ± 1.2	10.6 ± 1.7	n.s.			
Sit and reach (cm)	25.8 ± 5.2	31.5 ± 6.0	n.s.			
Standing broad jump (cm)	207.3 ± 23.7	225.6 ± 13.2	n.s.			
Handgrip (kg)	46.9 ± 10.6	54.6 ± 3.6	n.s.			
Sit-up (n)	43.9 ± 6.2	45.0 ± 9.7	n.s.			
Bent arm hang (s)	34.3 ± 18.9	40.8 ± 12.6	n.s.			
Shuttle run 5m (s) *	20.6 ± 1.3	19.5 ± 0.8	0.039	4.981	n.s.	n.s.
Shuttle run 20m (min) *	9.2 ± 1.7	11.1 ± 1.4	0.030	5.537	n.s.	n.s.

<u>**MOTOR COORDINATION (KTK)**</u>						
Optimist sailors **	**(n=16)**	**(n=7)**	**0.007**	**5.606**	**n.s.**	**n.s.**
Walking backwards (n)	53.3 ± 12.7	56.1 ± 9.1	n.s.			
Side Step (n) **	48.4 ± 6.9	62.6 ± 5.3	0.008	8.696	n.s.	n.s.
Side Jump (n) *	67.1 ± 7.5	82.3 ± 7.1	0.017	6.774	n.s.	n.s.
Dynamic hikers	**(n=15)**	**(n=9)**	**n.s.**			
Walking backwards (n)	55.6 ± 11.5	65.3 ± 5.0				
Side Step (n)	66.1 ± 7.5	64.3 ± 6.6				
Side Jump (n)	91.8 ± 9.8	89.8 ± 13.6				
<u>**SAILING-SPECIFIC TEST**</u>						
Optimist sailors	**(n=16)**	**(n=7)**				
Bucket test (s) *	301.3 ± 67.7	409.4 ± 51.1	0.050	3.212	n.s.	*
Dynamic hikers	**(n=15)**	**(n=9)**				
Bucket test (s) *	490.3 ± 64.7	600.1 ± 40.9	0.002	12.936	n.s.	*

*Note: * $p < 0.05$ ** $p < 0.01$*

Table 2 depicts the results of the stepwise discriminant analyses revealing the characteristics discriminating between elite and non-elite youth sailors. In the optimist group, 100.0 % of the elite sailors could be correctly classified by means of the motor coordination tests side step (SS) and side jump (SJ). In the dynamic hikers group, 88.9 % of the elite dynamic hikers could be correctly classified by means of the Bucket test.

Table 2: *Factors discriminating elite optimist sailors and dynamic hikers from non-elite optimist sailors and dynamic hikers respectively.*

	Wilks' lambda	p	Function Coefficients	r_c	Classification percentage
Optimist sailors (n=23)					
Side Step	0.475	0.000	0.114	0.828	100 % correctly classified
Side Jump	0.315	0.000	0.095		
(constant)			-12.839		
Dynamic hikers (n=24)					
Bucket test	0.509	0.000	0.018	0.700	88.9 % correctly classified
(constant)			-9.555		

Note: r_c = canonical correlation coefficient

Discussion

The present study aimed to determine indicators of sailing performance in 2 (age) groups of youth sailors by investigating the anthropometric, physical and motor coordination differences and factors discriminating between elite and non-elite male optimist sailors and young dynamic hikers. The main results indicated that 100.0 % of the elite optimist sailors and 88.9 % of the elite dynamic hikers could be correctly classified by means of two motor coordination tests (i.e. side step and side jump) and the Bucket test respectively. As such, strength- and speed-oriented motor coordination and isometric knee extension strength endurance can be identified as indicators of sailing performance in young optimist and young dynamic hikers respectively.

Both elite optimist sailors and dynamic hikers displayed a significantly older age than their non-elite peers. Despite their age difference, it was surprising that they did not indicate more years of experience in comparison to their non-elite peers. However, the elites reported to practice significantly more hours per week (table 1), which suggests that elite youth sailors gained more sailing experience (boat handling, tactical skills and environmental knowledge) in the same time period than their non-elite peers by spending more hours (sailing) on the water. Therefore, we can suggest that ‘practice hours per week’ is probably an important factor related to youth sailing success.

Because sailing is a weight-supported and weight-dependent (i.e. the body is used as a righting moment to provide leverage against the force of the wind) activity, specific height and body mass ranges for each Olympic class have been associated with success (Verdon et al., 2012). However, our results do not reveal significant differences in height or weight between elite and non-elite youth sailors (both optimist and dynamic hikers). Nevertheless, the elite optimist sailors tend to be somewhat taller and heavier than their non-elite peers. The elite dynamic hikers display an equal height but a heavier weight than their non-elite counterparts.

It is important to mention that our elite Flemish optimist sailors are still quite young compared to world’s top 20 elite optimists (table 3). Moreover, we can assume that years of experience is sufficient since earlier research showed that it is not too late to start optimist sailing at 10 or 11 years old (IODA, 2007, 2011). However, the Flemish elite optimist sailors clearly show too low practice amount (9.8 ± 2.2 hours/week) in comparison to the world's top 20 optimist sailors in 2003 (mean of 12.4 hours/week). This suggestion underlines once more the crucial role of practicing hours on the water for performance in optimist sailing. On the physical fitness tests, the elite optimist sailors did not score significantly better than their non-elite counterparts (table 1). This could be related with their general sports participation, although we did not dispose over this information. In comparison to the world's top 20 optimist sailors from 2003 (Gonzalez Munoz, 2003), these Flemish elite optimist sailors turned out to perform equally on the handgrip test and even better on sit and reach and sit-up test (table 3), indicating that the static strength, flexibility and core-stability is well-developed in our Flemish elite optimist sailors. Furthermore, the significant differences in side step (SS) (i.e. a more coordinative task) and side jump (SJ) (i.e. a more strength- and speed-orientated test) in our study (with age and maturity offset as no significant covariates) indicate the importance of strength- and speed-oriented coordination for optimist sailing performance. Moreover, based on SS and SJ tests, it is even possible to discriminate the better from the inferior optimist sailors, classifying the elite optimist sailors for 100.0 % in the correct group. Therefore, we suggest that strength- and speed-oriented coordination is an important indicator of optimist sailing performance. Compared to KTK-reference data of Flemish 11-year olds (Vandorpe et al., 2011a), we can establish that non-elite optimist sailors show a similar performance for SS and SJ test, but a slightly higher score for the walking backwards test (WB). As the elite optimist sailors were on average older than the non-elites, it is not possible to compare these sailors with a reference value. Anyway, these results point out the crucial role of motor coordination skill training throughout childhood in the development of elite sailors, similar to other youth athletes (Vandorpe et al., 2011b; Paillard et al., 2011).

Table 3: *Mean values ± SD (and range) from literature compared to those found in our study.*

Reference	Sailing level	n	Age (years)	Weight (kg)	Height (cm)	Start age (years)	Parent sailor?	Handgrip (kg)	Sit & Reach (cm)	Situps
Present study	Non-elite Ϙ	16	11.7 ± 1.1	37.6 ± 7.3	146.5 ± 10.9	8.1 ± 1.1		25.5 ± 8.1	19.9 ± 5.4	28.4 ± 5.0
Present study	Elite Ϙ	7	13.6 ± 1.2	46.4 ± 7.4	157.1 ± 8.7	9.3 ± 1.0		31.4 ± 4.0	28.1 ± 3.0	31.9 ± 3.8
IODA, 2002	2002 WT 10	10	- (12-15)	46.3 ± 4.9 (40-54)	159.8 ± 6.9 (149-170)					
Gonzalez Munoz, 2003	2003 WT 20	16	13.9	48.6	159.8		50 %	32.8	23	27.1
IODA, 2007	2007 WT 10	10 (2♀,8♂)	14.6 ± 0.7 (13-15)	47.3 ± 4.5 (41-54)	161.5 ± 3.8 (155-166)	8.6 ± 2.1 (4-11)	60 %			
IODA, 2011	2011 WT 10	10 (1♀,9♂)	14.3 ± 0.8 (13-15)	49.7 ± 4.3 (44-58)	165.7 ± 5.7 (158-175)	7.9 ± 1.7 (5-10)	70 %			

Note: Ϙ = optimist, WT = world top

Furthermore, elite dynamic hikers appear to have a better developed speed agility and aerobic endurance, as assessed from the 5m and 20m shuttle run respectively. These findings are in line with the physiological profile of hiking, considered to be a combined aerobic-anaerobic knee extension exercise with coordinative dynamic upper body movements (Cunningham & Hale, 2007; Spurway, 2007). As expected, both elite optimist sailors and dynamic hikers outperformed their non-elite peers on the Bucket test, measuring the knee extension strength endurance capacity. Since the elite youth sailors clearly showed more practice hours/week than their inferiors, it could be argued that this is due to a training adaptation. The discriminant analysis showed that 88.9 % of the elite dynamic hikers could be classified based on the Bucket test score. This is conform the observation that strength endurance, and in expansion maximum knee extension strength, is highly related to success in young dynamic hiking performance. It also emphasizes the importance of incorporating the development of maximum strength in training programs at young age (> 14 yrs) (Aagaard et al., 1998; Tan et al., 2006).

To our knowledge, this study is the first scientific insight into the characteristics of youth sailors. However, this study is not without limitations. First, it should be mentioned that the Körperkoordinationstest (KTK) normally consists of 4 subtests. However, we did not submit our youth sailor to the one-legged hopping test (Vandorpe et al., 2011a) because this test would be too time consuming and it was thought that this was of minor importance considering sailing exercise. Also, the KTK test battery is only validated up to 15 years which induces that we cannot draw conclusions from the motor coordination tests in dynamic hikers. Further, it is possible that difference in physical fitness parameters could in part be explained by differences in sports participation, besides sailing participation. Although a general sports participation questionnaire was given (printed version) and sent (digital version) to the sailors, there was insufficient response (15 % of the subjects) to include this issue in the data analysis and discussion. In addition, given the complex nature of the sport, the present study did not include several other factors contributing to sailing performance. We acknowledge the importance of psychological (such as personality, motivation and decision-making (Araújo et al., 2005)) and technical factors in the road to expertise.

Conclusion

This study underlines the importance of practice hours, knee extension strength endurance, and strength- and speed-oriented coordination as factors that are related to performance in optimist sailing. Moreover, the strength- and speed-oriented coordination can discriminate the elite from the non-elite optimist sailors and are therefore indicators of optimist sailing performance. In the dynamic hikers group, it can be concluded that practice hours, knee extension strength endurance, speed agility and aerobic endurance are important factors related to performance in dynamic youth sailing. The strength endurance test can discriminate the elite from the non-elite dynamic youth sailors. Therefore, we emphasize the importance of motor coordination skill training in optimist sailors (<15 yrs) and maximum strength training later on (>15 yrs) in order to increase their isometric knee extension strength endurance. In addition, we also advise aerobic fitness training and core-stability training as these parameters are fundamental for the further development of an athlete's physical capacity up to elite adult sailor.

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Study 2:

QUADRICEPS MUSCLE FATIGUE IN TRAINED AND UNTRAINED BOYS

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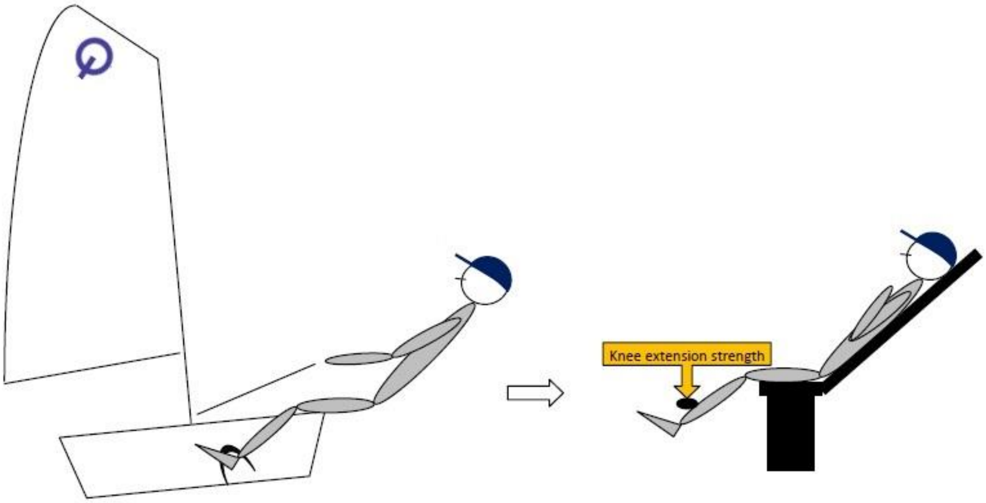

Abstract

This study aimed to explore muscle oxygen extraction and muscle activation pattern during bilateral intermittent submaximal isometric knee extensions by combining near infrared Spectroscopy (NIRS) and electromyography (EMG) measurements from the M. vastus lateralis. A group of highly specifically trained boys (youth sailors) (n = 10) and untrained matched controls (n = 10) performed 12 bouts of 90 s bilateral submaximal (30-40% MVC) isometric knee extension interspersed with 6s recovery-periods. Patterns of deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) were observed during each bout and the entire protocol. Reoxygenation index (RI) was assessed for each recovery period as the amplitude of deoxy[Hb+Mb]-decrease relative to amplitude of deoxy[Hb+Mb]-increase during each bout. Root mean square (RMS) and mean power frequency (MPF) were calculated for each bout as an average of the final 60 s. deoxy[Hb+Mb], RI, RMS and MPF were analyzed by repeated-measures ANOVA. Results indicated significantly higher deoxy[Hb+Mb]-increase and lower RI in specifically trained boys compared to untrained controls. These differences are presumably related to the differences in EMG-measurements which demonstrated lower RMS-increase and MPF-decrease for trained compared to untrained boys. In conclusion, specifically trained boys indicate delayed onset of muscle fatigue in comparison to untrained controls, which might be associated to the different pattern of muscle oxygen extraction or muscle activation pattern (i.e. a more accurate recruitment of slow-twitch fibers).

Introduction

Localized muscle fatigue during bilateral intermittent submaximal isometric knee extension exercise is a complex phenomenon, and could be defined as an inability of the muscle (group) to maintain the required or expected torque (Pääsuke et al., 1999). Fatigue mechanisms during isometric exercise can be influenced by numerous factors such as: exercise intensity (Crenshaw et al., 1997; De Ruiter et al., 2007; Boyas & Guével, 2011), muscle length (Kooistra et al., 2008; Boyas & Guével, 2011), number of extremities involved (Matkowski et al., 2011), number of muscles involved (Kooistra et al., 2006), age (Halin et al., 2003; Hatzikotoulas et al., 2009), gender (Kotzamanidis et al., 2006) and physical fitness level (Pääsuke et al., 1999; Lucia et al., 2000; Usaj, 2001; Halin et al., 2002; Usaj et al., 2007; Cohen et al., 2010).

Isometric contraction is characterized by restricted local blood flow (Moalla et al., 2006; De Ruiter et al., 2007; Vogiatzis et al., 2011), since the intramuscular pressure increases even at very low isometric contraction intensities (Crenshaw et al., 1997). Therefore, the delivery of oxygen and wash out of muscle metabolites may become limited, which affects the duration of such a contraction (Usaj, 2001). However, literature suggests that when fatiguing isometric contractions are performed at low levels (≤ 30% maximal voluntary contraction (MVC)), fatigue measured by electromyographic changes, is mainly due to neural changes, whereas at higher contraction levels (> 45% MVC) mainly metabolic factors contribute to fatigue (Crenshaw et al., 1997; Ratel et al., 2006; Hatzikotoulas et al., 2009).

Fatigue mechanisms have already been investigated by means of near infrared Spectroscopy (NIRS) or electromyography (EMG). NIRS-measured deoxygenation during isometric knee extension is influenced by both capillary blood flow and muscle oxygen uptake (Ferreira et al., 2005). However it is suggested that deoxygenation reflects capillary oxygen extraction rather than oxygen supply (Kime et al., 2003; Ferreira et al., 2005; Boone et al., 2010; Celie et al., 2012). For EMG-measurements during sustained submaximal isometric knee extension, a significant increase in root mean square (RMS) and decrease in mean power frequency (MPF) (Crenshaw et al., 1997; Moalla et al., 2006; Yamada et al., 2008) have been demonstrated, reflecting respectively an increase in additional motor unit recruitment and a decrease in the frequency of the EMG-spectrum, indicating muscle fatigue (Coburn et al., 2005). Recently, there has been an increased interest in combining NIRS and EMG to investigate muscle fatigue mechanisms during submaximal isometric knee extension exercise in adults (Yamada et al., 2008; Felici et al., 2009; Crenshaw et al., 2010). These research groups report a correlation between NIRS- and EMG-measurements suggesting a relationship between oxygen extraction and fatigue (Yamada et al., 2008; Felici et al., 2009). However, only a few studies have been conducted in a pediatric population (Moalla et al., 2006) or in adult populations with specifically trained and untrained subjects (Pääsuke et al., 1999; Halin et al., 2002).

By combining NIRS- and EMG-measurement, the purpose of this study was to get an insight into the performance limiting factors of bilateral intermittent submaximal isometric knee extension exercise at the muscle level by examining the time-course of deoxygenation, reoxygenation and myoelectrical manifestations (i.e. RMS and MPF) of the musculus Vastus Lateralis in young, highly specifically trained (sailors) and untrained boys. We hypothesized that (1) specifically trained boys will develop less muscle fatigue and higher deoxygenation and reoxygenation compared to untrained boys and that (2) the appearance of fatigue will be associated with changes in deoxygenation and reoxygenation.

Methods

Subjects

Twenty male subjects participated in this research: 10 specifically trained boys (international sailing level), highly trained in intermittent submaximal isometric knee extension exercise, and 10 untrained matched controls, performing no specific organised physical activities. Specifically trained boys and controls were matched for age (± 1 year), height (± 5 cm) and weight (± 5 kg). All subjects and their parents signed informed consent (according to (Harriss & Atkinson, 2011)), approved by the Human Research Ethics Committee of Ghent University Hospital. The subjects were instructed to perform no intensive exercise 48 hours before this test. The subjects' anthropometrics, practice hours/week and sailing experience are displayed in table 1.

Table 1: *Mean (± SD) of age, height, weight, body fat percentage, practice hours/week and sailing experience in specifically trained and untrained boys. (no significant differences were found)*

Group	Age (years)	Height (cm)	Weight (kg)	Body fat (%)	Practice (hours/week)	Experience (years)
Trained boys (n = 10)	14.0 ± 1.4	157.6 ± 11.4	44.4 ± 7.9	13.2 ± 3.7	9.6 ± 1.6	5.5 ± 1.8
Untrained boys (n = 10)	13.8 ± 1.3	162.2 ± 6.6	47.4 ± 8.2	11.8 ± 4.5		

Study design

Each subject performed 12 bouts of 90 s submaximal (30-40 % MVC) bilateral knee extension exercise (120° knee and hip angle) interspersed with 6 s recovery periods. Protocol settings were based on unpublished preliminary race analysis of the temporal pattern, contraction intensity and joint angles during competitive youth sailing (i.e. regattas).

Procedure

The subjects' height (anthropometer GPM, DKSH Switzerland) and weight (Electronic SECA, 815 Elegantia) were determined. Body fat percentage was measured by means of a skinfold caliper (Harpenden) and calculated by the method of Parizková (Parizková, 1961).

A 5-min standard warm-up on a cycle ergometer (Monark) and a short familiarization period of knee extension exercise on an isokinetic dynamometer (Biodex, system 2, USA) were performed 15 min prior to the actual protocol. The isokinetic dynamometer was set at 120° knee & hip angle and subjects performed three 5 s maximal voluntary bilateral isometric knee extension contractions, interspersed with 90 s of rest. The highest torque developed in the 3 attempts was regarded as the maximal voluntary contraction torque (MVC). Subjects were not fastened with straps to the isokinetic chair, but they were instructed to keep contact with the back support of the isokinetic chair. After 3 min rest, 30 & 40 % MVC were set as markers on the dynamometer screen and the subjects performed 12 bouts of 90 s bilateral isometric knee extension exercise between 30 and 40 % MVC (through visual feedback). The bouts were separated by 6 s of rest. The subjects were instructed to use both legs during the knee extension exercise. They were verbally encouraged by the researchers and all persisted throughout the entire protocol. The protocol is visually displayed in figure 1.

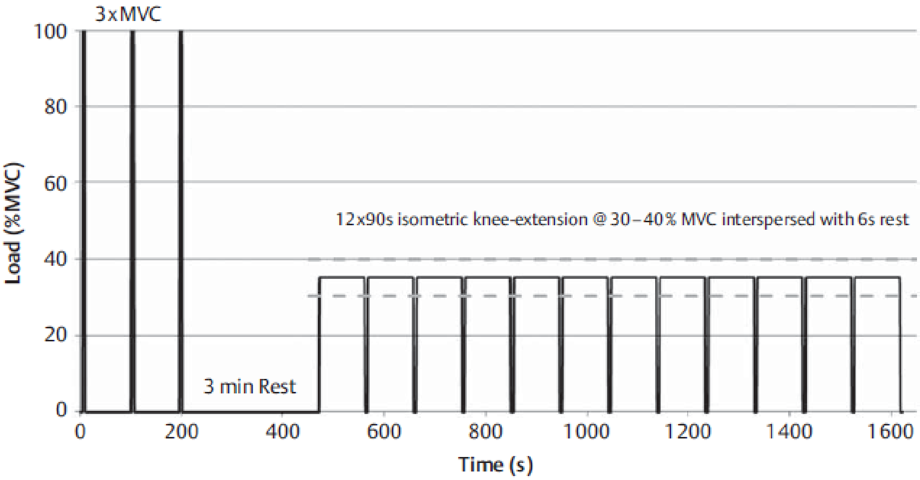

Figure 1: *Visual display of the test protocol: 3 attempts to maximal voluntary contraction (MVC), 3 min rest and 12 times 90 s knee extension exercise interspersed with 6 s rest.*

Measurements

Near infrared Spectroscopy (NIRS)

The NIRS-model Oxiplex TS^{TM} (ISS, Champaign, Illinois, USA) recorded continuously at a sampling frequency of 1 Hz, using a NIRS-probe consisting of 8 light-emitting diodes operating at wavelengths of 750 & 830 nm and a light detector, with a distance of 2.0 to 3.5 cm between the light source and the detector (Boone et al., 2010; Celie et al., 2012). The probe was positioned over the belly of the M. vastus lateralis, along the vertical axis of the right thigh and attached to the skin secured by Velcro straps and tape. Skin pen marks indicated margins of the probe and belt to check for any displacements of the probe during protocol. The probe was connected to a PC for data acquisition, analogue-to-digital conversion and subsequent analysis, based on the method of Belardinelli (Belardinelli et al., 1995). The baseline deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) was calculated as the average of 2 min rest seated in the dynamometer prior to protocol. This value was set as 100 %. From the start of the protocol, deoxy[Hb+Mb] was averaged in 10 s intervals (as a moving average) and expressed as a function of baseline deoxy[Hb+Mb] (Belardinelli et al., 1995). Reoxygenation index (RI) was determined immediately after each bout by setting out the amplitude of decrease in deoxy[Hb+Mb] at the end of 6 s rest (i.e. A2 in figure 2) to the amplitude of increase in deoxy[Hb+Mb] during 90 s knee extension exercise (i.e. A1 in figure 2). Reoxygenation index (%) is equal to A2, divided by A1 and multiplied by 100 (RI= A2/A1*100) (figure 2).

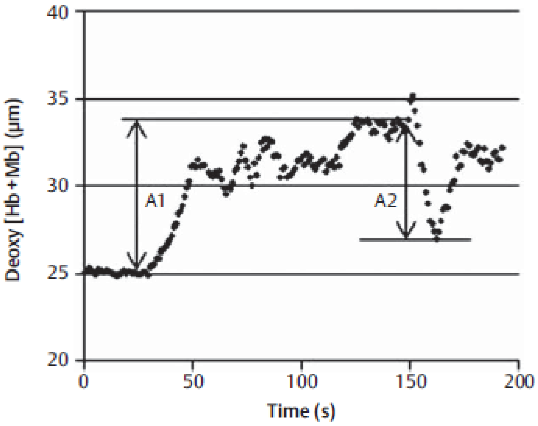

Figure 2: *Visual display of reoxygenation index (RI) calculation, as a function of A2/A1.*

Electromyography (EMG)

EMG (Noraxon) of the M. vastus lateralis was continuously recorded at sampling frequency of 1000 Hz using bipolar 34-mm-diameter Ag-AgCl electrodes (Blue Sensor, Danlee Medical Products, Inc., Syracuse, NY), placed almost on the same location of the M. vastus lateralis as the probe of the NIRS device (i.e. in the longitudinal axis of the NIRS-probe). Each electrode site was prepared by shaving, slight abrading and cleaning the site with an alcohol-ether-acetone solution (according to SENIAM recommendations). The EMG signal was checked for movement artefacts and the wires, connected to the electrode and were taped to the thigh of the subject. Myoelectric signals were relayed from the bipolar electrodes to a Telemyo device (Noraxon, Inc., Scottsdale, AZ) (Boone et al., 2010). The raw EMG signal was rectified, band-pass-filtered (Butterworth filter) and integrated using commercially available software (MyoResearch 2.10, Noraxon, Inc.) (Boone et al., 2010). The mean values of RMS and MPF were calculated for each bout as the mean of the final 60 s. The RMS- and MPF-values during the first bout were set to 100 % and the values during the following bouts were expressed relative to the first exercise bout.

Statistical analysis

Statistical computations were performed using SPSS® software (version 18; SPSS Lead Technologies Inc., Chicago, IL, USA). All data are presented as mean ± SD and independent sample t-tests were conducted to display significant differences between both groups for age, height, weight, body fat percentage, practice and experience. Bout 1 was analysed separately. Repeated measures ANOVA was used to determine whether changes of recorded deoxy[Hb+Mb] in time, were significant throughout bout 1. When a significant effect for deoxy[Hb+Mb] was detected within the 10s-deoxy[Hb+Mb]-values of the first bout these were compared 1 on 1 to a post-hoc test (student's t-test for paired observations, followed by the Bonferroni-type adjustment for multiple comparisons) (Vogiatzis et al., 2008). To indicate the bouts at which a significant difference between specifically trained and untrained boys could be seen in deoxy[Hb+Mb], RI, RMS or MPF, an independent sample T-test was used. Surprisingly, every variable showed a significant difference between specifically trained and untrained boys from bout 7 to the end of the protocol. Therefore, repeated measures ANOVA was used to determine significant main effects and interaction effects for all variables throughout the second half of the protocol (from bout 6 to 12). Further, the independent sample t-test was conducted to detect significant differences between both groups for the variables: Deoxy[Hb+Mb], RI, RMS and MPF at bout 12.

Results

Specifically trained boys (151.4 ± 43.9 N·m) showed no significantly higher maximal voluntary contraction torque (MVC), compared to untrained controls (153.3 ± 55.3 N·m). During 12 bouts of 90 s bilateral submaximal isometric knee extension interspersed with 6 s rest, deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) demonstrated a sequence of 12 identical cycles. Each one consists of 3 phases. As a sample, the 10s-values of bout 1 were statistically analyzed in figure 3. Significant within-effect for deoxy[Hb+Mb] (p = 0.001 & Wilks' Lambda = 9.017) was reported. Post-hoc comparison indicated first a significant ($p < 0.01$) increase in deoxy[Hb+Mb] and after approximately 30 s of muscle contraction a levelling off. The following 60 s, deoxy[Hb+Mb] remained in steady state with a significant ($p < 0.01$) decrease during the 6 s rest.

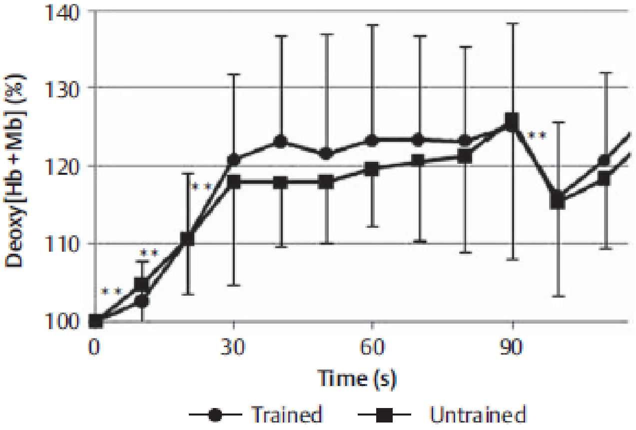

*Figure 3: Deoxy[Hb+Mb]-progress in time throughout bout 1. (within posthoc-test for deoxy[Hb+Mb]: *p < 0.05, **p < 0.01)*

Figure 4 shows the progress of respectively deoxy[Hb+Mb], reoxygenation index (RI), root mean square (RMS) and mean power frequency (MPF) in time. The independent sample t-test of 12 bouts deoxy[Hb+Mb], RI, RMS and MPF draws the attention to the second half of the protocol, where significant differences between both groups were detected. Therefore, repeated measures ANOVA was conducted only for the second part of the protocol (bout 6 to 12). Whereas this statistical analysis showed no interaction effect for deoxy[Hb+Mb] by group, it did show a significant effect between the groups ($p < 0.05$ & F = 5.461) which indicates a higher increase in deoxy[Hb+Mb] for specifically trained boys, compared to the untrained controls. Furthermore RI shows a significant effect between the groups ($p < 0.05$ & $F = 8.205$). Specifically trained subjects display a significantly lower RI than the untrained controls. Further, only a trend was found to between-group effect for RMS ($p = 0.087$ & $F = 3.272$). However, figure 4c displays clearly that untrained boys show a bigger increase in RMS, compared to specifically trained boys. Finally, a group-by-MPF interaction effect ($p < 0.05$ & $F = 3.878$) was found for MPF, which indicates a different progress in MPF for specifically trained boys, compared to untrained controls. Namely, MPF decreased for untrained controls whereas it stayed in a more or less steady state for specifically trained boys.

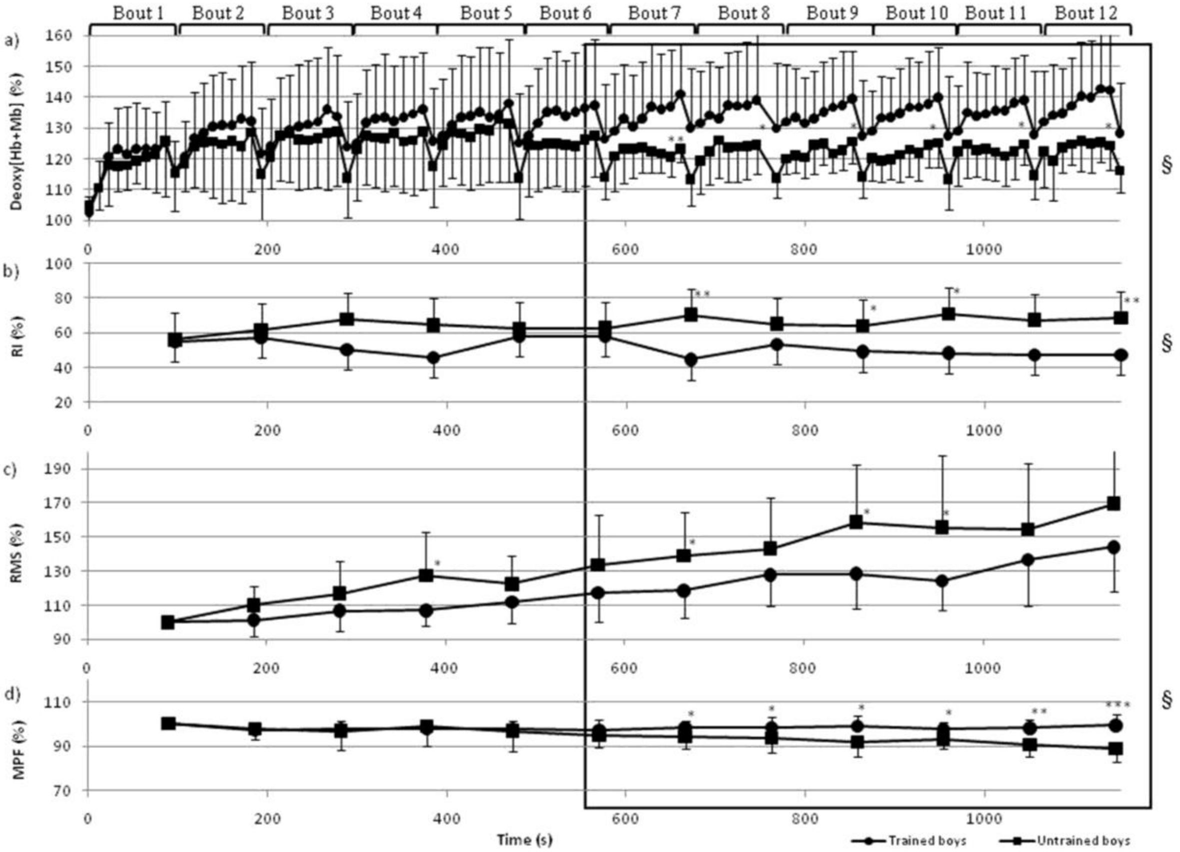

Figure 4: *a) Deoxy[Hb+Mb], b) reoxygenation index (RI), c) root mean square (RMS), d) mean power frequency (MPF) progress in time. (independent sample t-test: *p < 0.05, **p < 0.01, ***p < 0.001) (repeated measures ANOVA: § significant between-group effect)*

Table 2 indicates (at bout 12) a significantly higher increase in deoxy[Hb+Mb] ($p = 0.016$ & $t = -2.766$), a significant lower decrease in MPF ($p < 0.001$ & $t = -4.356$) and a significantly lower RI (p = 0.003 & t = 3.479) for specifically trained subjects compared to untrained controls. However, there were no significant differences found in the increase of RMS.

***Table 2:** Deoxy[Hb+Mb], reoxygenation index (RI), percentage root mean square (RMS) and mean power frequency (MPF) at protocol-end (bout 12) in specifically trained and untrained boys.*

Group	Deoxy[Hb+Mb]$_{bout12}$ (%)	RI$_{bout12}$ (%)	RMS$_{bout12}$ (%)	MPF$_{bout12}$ (%)
Trained boys (n = 10)	142.3 ± 18.5 *	47.4 ± 11.5 **	144.1 ± 26.2	99.3 ± 5.0 ***
Untrained boys (n = 10)	124.4 ± 7.8 *	68.5 ± 15.2 **	169.5 ± 54.6	88.9 ± 5.7 ***

*Note: Independent sample t-test: *p < 0.05, **p < 0.01, ***p < 0.001*

Discussion

The aim of this study was to investigate performance limiting factors at muscle level during bilateral intermittent submaximal isometric knee extension by examining the time course of deoxygenation, reoxygenation and myoelectrical manifestations of the M. vastus lateralis, by means of near infrared Spectroscopy (NIRS) and electromyography (EMG) in a pediatric population. We also investigated whether there is a different response at muscle level between highly specifically trained and untrained boys. The major findings of this study demonstrate that specifically trained boys show a higher increase in deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) and surprisingly a lower reoxygenation index (RI), compared to untrained controls. Also, the slower rate of increase in root mean square (RMS) and decrease in mean power frequency (MPF) supports the hypothesis that specifically trained subjects develop muscle fatigue slower compared to untrained controls, due to a specific response at muscle level.

In the present study, it was demonstrated that during each bout of the bilateral submaximal isometric knee extension exercise, there was a gradual increase in deoxy[Hb+Mb], followed by a steady state and an sharp decrease in deoxy[Hb+Mb] at the onset of muscle relaxation. It should be noted that deoxy[Hb+Mb] has frequently been used to express the degree of microvascular oxygen (O_2) extraction (Ferreira et al., 2005; Boone et al., 2010; Celie et al., 2012) and deoxy[Hb+Mb] is less affected by changes in blood volume under the NIRS probe during exercise compared to oxygenated hemoglobin and myoglobin concentration (oxy[Hb+Mb]) (Ferreira et al., 2005).

Statistical analysis of bout 1 confirmed the appearance of these 3 phases during this exercise. At the onset of submaximal isometric muscle contraction, the balance between O_2-supply and O_2-demand is clearly disturbed. To minimize the O_2-deficit, deoxy[Hb+Mb] increased sharply as an indication of increase in O_2-extraction. Subsequently, the balance is restored as deoxy[Hb+Mb] levels off to reach a steady state phase. Finally, as a result of the muscle relaxation (6 s) and a decreased intramuscular pressure, we suggest that there is a sudden outflow of deoxygenated hemoglobin and inflow of oxygenated hemoglobin (i.e. reoxygenation of the tissue under the NIRS-probe). Unfortunately, this study has no reliable measurements of muscle perfusion.

At this moment, there is no consensus about whether blood perfusion is occluded during the submaximal (30 to 40 % MVC) isometric knee extension exercise. Several earlier studies (Crenshaw et al., 1997), have suggested that during submaximal knee extension exercise lower than 40 % MVC, blood flow is not occluded. On the other hand, De Ruiter & colleagues (2007) registered in M. vastus lateralis already an arterial occlusion from 25 % MVC torque (at 90° knee and hip angle) and reported that increased fiber-pennation angle, and thus decreased knee angle, leads to a higher intramuscular pressure. Surprisingly, this muscle load which would contribute to muscle occlusion, is quite low. Knowing that intramuscular pressure is higher in deep parts than in superficial parts of the muscle (Sejersted et al., 1984), it can be suggested that when superficial occlusion is measured from NIRS-variables, capillary blood flow into the muscle is certainly occluded. However, in this study, no valid measurements of intramuscular pressure or blood flow were done. Though, the steady state phase in deoxy[Hb+Mb]-pattern suggests that capillary blood flow in the muscle is probably not occluded. This is in line with the results of the only pediatric study (Moalla et al., 2006) that investigated NIRS and EMG during submaximal knee extension exercise, since Moalla & co-workers (2006) reported an ischemia at or above 50 % MVC isometric knee extension (at 90° knee and hip angle), due to increased intramuscular pressure. However, as demonstrated above, no consensus has been reached on the contribution of restricted blood circulation to the development of fatigue during submaximal isometric knee extension exercise in adults and only little research (Moalla et al., 2006) in this direction has been done in a pediatric population.

Throughout the entire protocol, specifically trained boys display a higher deoxy[Hb+Mb]-increase compared to untrained controls. In fact, they also show a continuous increase in deoxy[Hb+Mb], whereas untrained controls indicate only a slight increase in deoxy[Hb+Mb] until bout 6 and a steady state in deoxy[Hb+Mb] from bout 6 to 12. Thus, differences in deoxy[Hb+Mb] between both groups are present especially from bout 6 to 12. The higher deoxy[Hb+Mb]-increase in specifically trained subjects suggests that they show a higher increase in capillary O_2-extraction, compared to untrained controls. This is in line with the results of Usaj (2001) which showed that after 4 weeks of endurance training an increase in relative deoxygenated hemoglobin concentration and endurance time during sustained submaximal isometric handgrip exercise (at 30 % MVC) was visible. The author suggested that a certain number of capillaries may open as a result of isometric endurance training, increasing O_2 consumption capacity as a result of increased O_2 availability. Furthermore, a higher muscle fiber oxidative capacity (i.e. higher muscle capillary density, higher mitochondrial density, higher mitochondrial oxidative enzyme activity, higher glycogen stores, higher creatine phosphate stores and more myoglobin concentration) is suggested due to endurance training adaptation (Pääsuke et al., 1999; Häkkinen et al., 2003). Additionally, the neuromuscular activation (i.e. muscle fiber recruitment) pattern is changed due to training adaptation (Maïsetti et al., 2006; Boyas et al., 2009). We suggest that the higher deoxy[Hb+Mb]-increase in specifically trained compared to untrained boys is probably related to the different muscle fiber recruitment, because changes in RMS and MPF are largely in parallel to those of deoxy[Hb+Mb] (figure 4). In the specifically trained boys, the RMS-increase is not significantly, though remarkably lower and the MPF-decrease is significantly lower than for untrained controls. This expresses less fatigue development and lower additional motor unit recruitment for specifically trained subjects compared to untrained controls (Coburn et al., 2005). As a result of many hours of quasi-isometric knee extension exercise during sailing training (on average 5.5 ± 1.8 years of circa 9.6 ± 1.6 hours a week), it is suggested that specifically trained boys acquired slow-twitch (ST) fibers with a higher oxidative capacity (Pääsuke et al., 1999; Häkkinen et al., 2003) than those of the untrained controls. This results in a higher strength endurance capacity but not in a higher maximal strength capacity (Cohen et al., 2010). This is confirmed by the results of this study. Briefly, it is possible that endurance-trained boys will be able to modify their muscle activation pattern (Mitchell et al., 2011), presumably by recruiting primarily ST fibers (Lucia et al., 2000), indicated by the continuous increase in deoxy[Hb+Mb] throughout the protocol, whereas for the same period of time, untrained controls will have to recruit faster their more fatigable fast-twitch (FT) fibers, indicated by the steady state in deoxy[Hb+Mb] during the second half of the protocol.

Since specifically trained subjects exhibited a higher increase in capillary O_2-extraction compared to untrained controls, it is very surprising that specifically trained boys displayed a lower RI compared to the controls. However, it is important to note that RI doesn't reflect muscle reoxygenation, but reoxygenation of [Hb+Mb] under the NIRS-probe, situated in small capillary blood vessels. In line with Kime & colleagues (2003), the slower RI for specifically trained children is presumably due to the higher oxidative capacity and thus the higher capillary O_2-extraction from the M. vastus lateralis of specifically trained boys compared to that of untrained controls. As a consequence, the O_2-gradient from capillary blood to myocyte at the onset of blood reperfusion will be higher in specifically trained boys compared to untrained controls. Consequently, the trained subjects will be able to compensate the O_2-imbalance in the M. vastus lateralis itself more rapidly, but this will result in a slower reoxygenation of [Hb+Mb] under the NIRS-probe, because of a very fast capillary O_2-extraction of [Hb+Mb]. Additionally, results confirm that the speed and magnitude of capillary O_2-extraction during this type of exercise is a very important factor influencing the RI (Kime et al., 2003).

To our knowledge, this is the first study to examine modification in both EMG and NIRS activity in trained and untrained children during bilateral intermittent submaximal isometric knee extension exercise. However, the study shows some limitations, inherent to NIRS- and EMG-measurements. First of all, earlier studies (Kime et al., 2003) with NIRS performed an arterial occlusion as physiological scale to determine the level of deoxygenation in adult participants. However, this method is very painful, especially for leg occlusion, and rarely used in pediatric populations. Therefore, we set the baseline value at 100 % deoxy[Hb+Mb] and expressed deoxy[Hb+Mb] relative to the baseline value. Also, since NIRS-techniques rely on light penetration to the tissue which is mainly absorbed by chromophores (Moalla et al., 2006), we assume that no difference can be shown between adults and children. It would be interesting in the future to assess methodologies of the NIRS signal in both children and adults. Secondly, the two probes, metabolic and electromyographic (NIRS and

EMG), were as close as possible to each other but not exactly on the same muscle proportion. EMG-measurement provides a good representation of total muscle recruitment (Coburn et al., 2005). However, NIRS shows regional differences in oxygenation (Crenshaw et al., 2010). In addition, NIRS-measurement allows the investigation of only a few cubic centimeters of the superficial muscle area, where predominantly FT fibers are situated (Knight & Kamen, 2005). Unfortunately, this technical limitation of NIRS in general cannot be solved. In addition, we strongly advise additional investigations with suitable techniques (blood metabolites and electrolytes concentration measurement) combined with NIRS and EMG to get more insight into the mechanisms that limit the bilateral intermittent submaximal isometric knee extension.

In conclusion, our findings indicate that specifically trained boys show at the muscle level a different response to bilateral intermittent submaximal isometric knee extension exercise compared to the untrained controls. The differences in deoxy[Hb+Mb] might reflect a different pattern of muscle O_2-extraction, presumably due to a higher oxidative capacity of the ST fibers in their M. vastus lateralis and a more accurate neuromuscular fiber activation pattern, due to training adaptations at muscle level. As a consequence, specifically trained boys showed a delayed onset of muscle fatigue during this specific submaximal bilateral isometric knee extension exercise.

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Study 3:

CARDIORESPIRATORY AND MUSCULAR RESPONSES TO SIMULATED UPWIND SAILING EXERCISE IN OPTIMIST SAILORS

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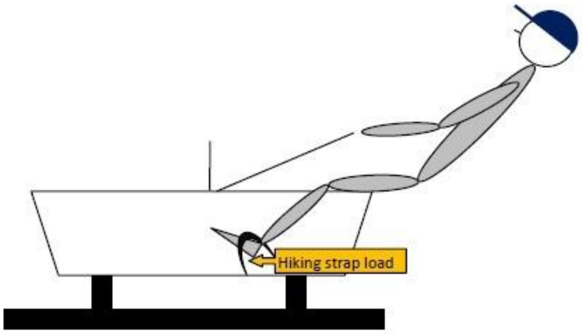

Abstract

The aim of this work was to gain more insight into the cardiorespiratory and muscular (M. vastus lateralis) responses to simulated upwind sailing exercise in 10 high level male and female Optimist sailors (10.8 to 14.4 years old). Hiking strap load (HSL) and cardiorespiratory variables were measured while exercising on a specially developed Optimist sailing ergometer. Electromyography (EMG) was used to determine Mean Power Frequency (MPF) and Root Mean Square (RMS). Near-infrared Spectroscopy (NIRS) was used to measure deoxygenated Hemoglobin and Myoglobin concentration (deoxy[Hb+Mb]) and reoxygenation. Results indicated that HSL and integrated EMG of the Vastus Lateralis muscle changed in accordance with the hiking intensity. Cardiorespiratory response demonstrated an initial significant increase and subsequently steady state in oxygen uptake (VO_2), ventilation (V_E) and heart rate (HR) up to circa 40 % VO_2peak, 30 % $V_E$peak and 70 % HR_{peak} respectively. At muscle level, results showed that highly trained Optimist sailors manage to stabilize the muscular demand and fatigue development during upwind sailing (after an initial increase). However, approaching the end of the hiking exercise, the MPF-decrease, RMS-increase and deoxy[Hb+Mb]-increase possibly indicate the onset of muscle fatigue.

Introduction

In every competitive sailing course, two thirds of total racing time is spent on sailing upwind (Blackburn, 1994; Legg et al., 1999). Sailing upwind consists mainly of the demanding *hiking* technique which is interspersed several times by a tack (i.e., the maneuver of turning between starboard and port tack whereby the sailor has to change from the one edge to the other). Hiking is used to counterbalance the tilting moment, created by the wind that blows into the sail, in order to keep optimal boat speed (Legg et al., 1999). This is done by hooking the feet under a hiking strap, placing the middle of the thigh on edge of the boat and extending the upper body outside the boat to create a counterweight that balances the boat. Earlier research identified this hiking-technique as a quasi-isometric exercise mainly employing the M. vastus lateralis (Spurway, 2007; Vogiatzis et al., 2011), which therefore probably contributes most to fatigue during sailing upwind (Tan et al., 2006; Spurway, 2007; Vogiatzis et al., 2011).

In competitive dinghy sailing, young boys and girls all compete together in the Optimist class up to the age of 15. The rationale behind this competitive class rule is that the dimensions of the Optimist dinghy (2.30m length and 1.15m width) induce optimal weight and height to perform in this dinghy (Rodio et al., 1999; Callewaert et al., 2013a). This ensures that on the one hand children (probably early maturing) who outgrow this boat already before the age of 15, need to switch to an adult dinghy earlier than described by the class rule and on the other hand that children (probably late maturing) who do not outgrow this boat till the age of 15, nonetheless will have to switch to an adult dinghy at the age of 16. Although worldwide, more than 130,000 children are sailing the Optimist (some very frequently and at high level), scientific literature lacks information on the physiology of youth (Optimist) sailing. The physiological responses to upwind sailing have already been extensively investigated in adult populations by both on-water (Vogiatzis et al., 1995; Portier & Guézennec, 2002; Castagna et al., 2004; Castagna & Brisswalter, 2007) and simulation studies (Maïsetti et al., 2006; Cunningham & Hale, 2007; Vangelakoudi et al., 2007; Vogiatzis et al., 2008, 2011; Boyas et al., 2009). However, only one study demonstrated the on-water cardiorespiratory responses in a pediatric population (Rodio et al., 1999). As the focus in sailing physiology research has recently shifted from the cardiorespiratory more to the muscular level, it would be of interest to apply

Electromyography (EMG) and Near-infrared Spectroscopy (NIRS) (Moalla et al., 2006) recordings in a pediatric sailing-specific situation as well. In this way, more insight into the muscle fiber recruitment and oxygen extraction strategy will be established in young sailors. Armatas & colleagues (2010) indicated in their study that men and boys respond differently to fatigue and recovery after a repeated intermittent maximal isometric knee-extensor fatigue protocol (i.e. boys are more fatigue resistant in comparison to adults, probably due to a more limited inhibition of the boys' agonist muscles). Accordingly, we assume the mechanisms that contribute to muscle fatigue during upwind sailing are different in boys compared to adults as well. Therefore, it is essential to investigate the cardiorespiratory and muscular responses during simulated upwind sailing exercise (which is considered to be a repeated intermittent quasi-isometric knee-extensor fatigue protocol) not only in adults, but also in children or adolescents.

The purpose of this study was to investigate the cardiorespiratory and muscular responses to simulated upwind sailing exercise in highly trained Optimist (adolescent) sailors in order to gain more insight into the mechanisms contributing to the onset of muscle fatigue.

Methods

Participants

Ten high level Optimist (6 male and 4 female) sailors (from 10.8 to 14.4 years old), all member of the Flemish national Optimist squad (selected and trained by national youth coaches in order to compete in international tournaments and championships), were invited to participate in this study. All participants and their parents gave informed consent and were told that they could withdraw from the study at any time. The study was carried out in accordance with ethical standards in sport and exercise science research (Harriss & Atkinson, 2011) and cleared by the Human Research Ethics Committee of Ghent University Hospital (Ghent, Belgium). The participants' height (anthropometer GPM, DKSH Switzerland), sitting height (Suisse stadiometer), weight (Electronic SECA weighing machine) and 10 skinfold thicknesses (Harpenden skin fold caliper) were measured. Body fat percentage was calculated by the method of Parizková (Parizková, 1961) and maturity offset (MO) and age at peak height velocity (PHV) were calculated according to Mirwald & co-workers (2002). Sailing experience (years) and training volume (hours/week sailing and physical dry-land training) were recorded by a questionnaire. All participants performed both an incremental cycling test (ICT) till exhaustion and an upwind sailing test (UST) within a period of 2 weeks to ensure that the level of physical fitness did not change. The participants were asked to abstain from strenuous exercise for at least 48 h before both their visits to the laboratory.

Optimist ergometer construction

As it is nearly impossible to use Near-infrared Spectroscopy (NIRS) and Electromyography (EMG) during on-water sailing, an upwind sailing ergometer and protocol that simulates as accurately as possible the on-water upwind sailing exercise was developed (Callewaert et al., 2013b). The Optimist ergometer was constructed by fixing an Optimist dinghy on a vast undercarriage in a rigid and perfectly horizontal way. Mast and sail were removed from the boat. Only rudder, mainsheet and hiking straps were kept. Rudder and mainsheet arrangement were rigged to provide resistance to match that of an Optimist dinghy in winds of >15 knots (based on preliminary on-water research which investigated the load on rudder and mainsheet (unpublished data)); elasticized rope provided resistance equal to 15 N rudder load and a 10mm shock cord (Cunningham & Hale, 2007) was used to put 80 N resistance on the mainsheet (Callewaert et al., 2013b). Resistance on the rudder and mainsheet was validated using weight-calibration. In addition, a load cell (A.L. Design type W2, Buffalo, NY, USA) developed in our department (Malcolm et al., 2009), attached to the hiking straps, was used to measure the hiking strap load (HSL). Before each test, the load cell was calibrated using weights of up to 60 kg. Before the upwind sailing test protocol, the participants were asked to perform 3 times at each side a 5 s flat-out maximal static hiking exercise interspersed with 60 s of rest. During this maximal contraction, HSL was determined as maximal hiking strap load (HSL_{max}).

Incremental cycling test (ICT)

Each participant performed a continuous incremental cycling exercise (i.e., ramp protocol) on an electromagnetically braked cycle ergometer (Excalibur Sport; Lode, Groningen, The Netherlands). The actual ramp increase was preceded by 3 min of rest on the cycle ergometer and 3 min of baseline cycling at 40 W (Boone et al., 2010). Then, power output increased linearly and continuously with a rate of 0.25 $W \cdot s^{-1}$. The participants were instructed to cycle at 65-70 revolutions per minute (rpm) (Boone et al., 2010). The instantaneous pedal rate was continuously visualized on a display connected to the electromagnetic cycle ergometer, so that the participants were informed about the cadence (rpm) throughout the exercise tests. The test was terminated when the participants could no longer maintain the instructed pedal rate, despite strong verbal encouragement.

Upwind Sailing Test (UST)

The aim was to accurately simulate the on-water upwind sailing exercise. Development of this ergometer and protocol was based on preliminary on-water research (unpublished data). First, the UST protocol sought to replicate body movements associated with upwind sailing in the Optimist class by asking the participants to imitate (as they experience in reality) the movements in a synchronized upwind sailing video, projected on the wall in front of them. The video was assembled from regatta recordings from national Optimist sailors. Second, in order to indicate the required hiking intensity, the video contained subtitles from which the participants were able to follow instructions such as *maximal hiking, hard hiking, average hiking, light hiking or tacking*. By a combination of these two indicators, the participants constantly received instructions about what to do and how hard to hike. Furthermore, the protocol comprised 17 hiking bouts of 90 s interspersed with 10 s to tack (= 28 min and 20 s of upwind sailing exercise in total). Each bout consisted of 10 s of *maximal hiking*, 30 s of *light hiking*, 20 s of *average hiking*, 20 s of *hard hiking* and 10 s of *maximal hiking* respectively (Callewaert et al., 2013b). The hiking intensity pattern was set in this way to represent the greater hiking exercise performed each time preceding and following every tack in order to facilitate preparation to tack or to increase boat speed after tacking. Nevertheless, the first and last bout were different in hiking intensity compared to the other bouts (Callewaert et al., 2013b). The first bout consisted of 60 s *maximal hiking* and 30 s *hard hiking* representing the greater hiking exercise required in order to immediately take the lead of the fleet. Equally, the last bout also consisted of a higher hiking exercise (i.e., 10 s *maximal hiking*, 30 s *average hiking*, 20 s *hard hiking* and 30 s *maximal hiking*) to represent the effort sailors make to fetch the mark as fast as possible. During the sailing protocol, the young sailors were given feedback in order to accurately perform the sailing movements and intensities that were asked on video images.

Measurements

During ICT, oxygen uptake (VO_2), ventilation (V_E) and respiratory exchange ratio (RER) were measured continuously on a breath-by-breath basis using a computerized O_2-CO_2 analyzer-flowmeter combination and averaged during 10-s intervals (Jaeger Oxycon Pro, Höchberg, Germany) (Boone et al., 2010). Before each test, the gas analyzers and volume transducer were calibrated. Heart rate (HR) was measured with a Polar RS400. Peak Power output, VO_2peak, $V_E$peak and HR_{peak} were determined for every participant as the highest value at exhaustion (table 1). VO_2peak was scaled to the absolute body weight, the relative body weight (i.e. in $ml \cdot min^{-1} \cdot kg^{-0.67}$) (Rogers et al., 1995) and the fat free mass (Akkerman et al., 2010).

During UST, rate of perceived exertion (RPE) (6-20 Borg-scale) (Borg, 1982), heart rate (HR) (Polar RS400), systolic (SBP) and diastolic blood pressure (DBP) (full-automatic sphygmomanometer: KD-5915) were measured. These parameters were determined at rest and at hiking bouts 3, 5, 7, 9, 11, 13, 15 and 17 (i.e., immediately after the 10 s *maximal hiking*). Mean Arterial Blood Pressure (MAP) was calculated as DBP + 1/3*(SBP – DBP). VO_2, V_E and RER were measured as earlier described in the ICT. VO_2, V_E and HR were presented as measured values and as relative values to their VO_2peak, $V_E$peak and HR_{peak} respectively. Near-infrared Spectroscopy (NIRS) and Electromyography (EMG) were continuously recorded.

Surface Electromyography (sEMG)

The wireless EMG-system ‘Zero wire EMG (Aurion)’ was used to continuously record integrated EMG at a sampling frequency of 1000 Hz by using bipolar 34-mm-diameter Ag-AgCl electrodes (Blue Sensor, Danlee Medical Products, Inc., Syracuse, NY), placed almost on the same location of the Musculus Vastus Lateralis as the probe of the NIRS device (i.e., in the longitudinal axis of the NIRS-probe). Each electrode site was prepared following SENIAM recommendations (Callewaert et al., 2013a). Myoelectric signals were checked for movement artefacts and were relayed to a Telemyo device (Noraxon, Inc., Scottsdale, AZ). The raw EMG signal was rectified, band-pass-filtered (Butterworth filter) and integrated using commercially available software (MyoResearch 2.10, Noraxon, Inc.) (Callewaert et al., 2013a). Before the UST, the participants were asked to perform 3 times at each side a 5 s flat-out maximal hiking exercise. During this maximal effort, both HSL and EMG were determined as maximal hiking strap load (HSL_{max}) and Maximal Voluntary Contraction (MVC) respectively. MVC was set as 100% and integrated EMG ($_{i}EMG$) was set in relation to MVC. Root mean square (RMS) (as an expression of motor unit recruitment (Coburn et al., 2005)) and mean power frequency (MPF) (as an expression of fire frequency and muscle fatigue development (Coburn et al., 2005)) were calculated for each bout as the mean of the final 10 s. The RMS- and MPF-values during the first bout were set to 100% and the values during the following bouts were expressed relative to the first exercise bout (Callewaert et al., 2013a).

Near-infrared spectroscopy (NIRS)

The Oxiplex TS^{TM} (ISS, Champaign, Illinois, USA) was used for NIRS-registration (Callewaert et al., 2013a). This NIRS-probe was positioned over the belly of the M. Vastus lateralis, along the vertical axis of the right thigh and attached to the skin secured by Velcro straps and tape. Skin pen marks indicated margins of the probe and belt to check for any displacements of the probe during the exercise protocol (Callewaert et al., 2013a). Deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) was observed as an expression of oxygen extraction (Boone et al., 2010; Celie et al., 2012; Callewaert et al., 2013a). Preceding the UST protocol, an arterial occlusion was conducted on the upper leg by inflating a cuff around the right thigh to 260 mmHg. The amplitude of the deoxy[Hb+Mb] occlusion response (i.e., the difference between the highest 10 s average of deoxy[Hb+Mb] during the occlusion and the 30 s average of deoxy[Hb+Mb] preceding the occlusion) was used as an index for maximal O_2-extraction and was set as 100%. The changes in deoxy[Hb+Mb] during the UST were expressed in relation to this amplitude (Celie et al., 2012). In addition, reoxygenated hemoglobin and myoglobin concentration (reoxy[Hb+Mb]) was also calculated immediately after each bout by setting out the amplitude of the decrease in deoxy[Hb+Mb] during the tack (i.e., A2 in figure 1) to the amplitude of deoxy[Hb+Mb] occlusion response (i.e., A1 in figure 1). Reoxy[Hb+Mb] (in % $deoxy[Hb+Mb]_{max}$) is equal to A2, divided by A1 and multiplied by 100 (reoxy[Hb+Mb] = A2 / A1 * 100) (figure 1).

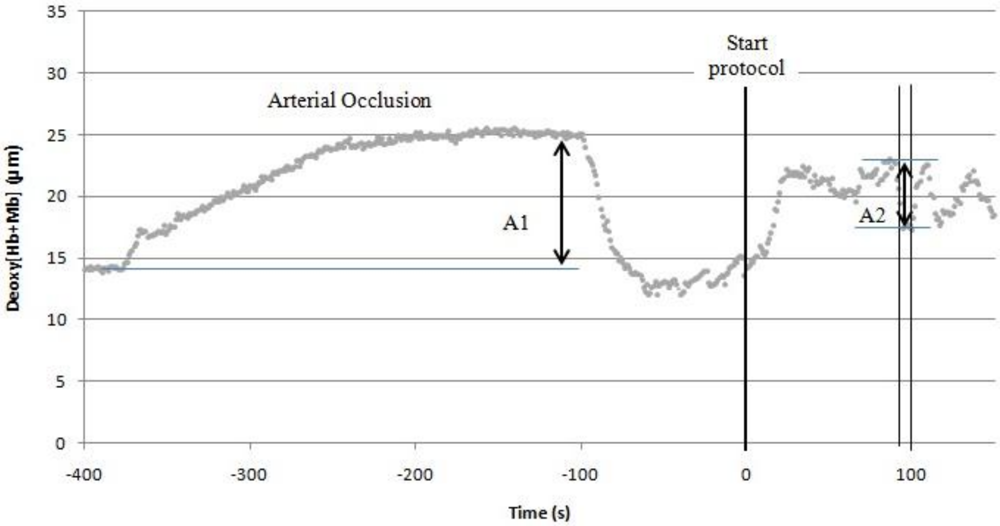

Figure 1: *Visual display of deoxy[Hb+Mb] pattern and reoxygenation (reoxy[Hb+Mb]) calculation, as a function of A2/A1.*

Statistical analyses

Statistical computations were performed using SPSS software. Normal distribution was checked and found for each variable. All data were presented as means ± standard deviation (SD). Differences in training history, anthropometry and incremental cycling exercise data between boys and girls were analyzed by means of non-parametric Mann-Whitney U Test. One-way analysis of variance (ANOVA) with repeated measures was conducted to determine whether significant changes in HSL, VO_2, V_E, RER, HR, DBP, SBP, MAP and RPE could be detected. For the different intensities of HSL, VO_2, V_E and RER bout 1, 5, 11, 15 and 17 were included in the statistical analysis. For HR, DBP, SBP and MAP pre-measurement (at rest), bout 5, 11, 15 and 17 were included. For RPE bout 5, 11, 15 and 17 were included. Also, one-way analysis of variance (ANOVA) with repeated measures was conducted to determine whether changes in the recorded MPF, RMS, deoxy[Hb+Mb], reoxy[Hb+Mb] and HR were significant throughout protocol (bout 1, 3, 5, 7, 9, 11, 13, 15 and 17 were included). When a significant effect was detected, post hoc comparisons were carried out (Student’s t-test for paired observations, followed by the Bonferroni-type adjustment for multiple comparisons) (Vogiatzis et al., 2008; Callewaert et al., 2013a). Statistical significance for all analyses was set at $p < 0.05$.

Results

Table 1 shows a mean training volume of 8.6 ± 2.7 hours/week, age of 13.2 ± 1.0 years and maturity offset of 0.9 ± 0.7 years before age at peak height velocity (PHV). The girls' mean age was 12.6 ± 1.4 years (variation from 10.8 to 14.0) and the boys' mean age was 13.6 ± 0.6 (variation from 12.6 to 14.4). The maturity offset ranged between 0.3 and 2.5 before their age at PHV. There was a significant difference between boys and girls in maturity offset ($p = 0.038$), weight ($p = 0.038$), peak power output ($p = 0.019$) and VO_2peak ($p = 0.010$).

Table 1: *Training history, anthropometry and incremental cycling exercise data (mean ± SD) of 10 Optimist sailors.*

Variable	Optimist sailors (n=10)	Boys (n=6)	Girls (n=4)	p
Training history:				
Experience (years)	4.8 ± 1.3	4.8 ± 1.5	4.8 ± 1.3	n.s.
Training volume (hours/week)	8.6 ± 2.7	9.8 ± 2.2	6.8 ± 2.5	n.s.
Anthropometry:				
Age (years)	13.2 ± 1.0	13.6 ± 0.6	12.6 ± 1.4	n.s.
Age at PHV (years)	14.2 ± 0.6	14.2 ± 0.6	14.1 ± 0.6	n.s.
Maturity Offset (years)	-0.9 ± 0.7	-0.6 ± 0.3	-1.5 ± 0.8	0.038
Height (cm)	161.7 ± 10.4	166.5 ± 10.2	154.3 ± 5.6	n.s.
Weight (kg)	44.8 ± 8.1	49.1 ± 6.7	38.4 ± 5.3	0.038
Body Fat (%)	15.4 ± 4.5	13.3 ± 4.0	18.6 ± 3.5	n.s.
Incremental cycling exercise:				
Peak Power output (Watt)	206.7 ± 38.7	226.6 ± 37.9	176.8 ± 10.8	0.019
Peak Power output ($Watt \cdot kg^{-1}$)	4.77 ± 0.45	5.0 ± 0.4	4.4 ± 0.2	0.012
VO_2peak ($l \cdot min^{-1}$)	2.4 ± 0.6	2.8 ± 0.4	1.8 ± 0.2	0.020
VO_2peak ($ml \cdot min^{-1} \cdot kg^{-1}$)	50.1 ± 5.6	57.0 ± 3.1	47.3 ± 1.8	0.010
VO_2peak ($ml \cdot min^{-1} \cdot kg^{-0.67}$)	184.0 ± 23.4	199.8 ± 14.2	160.2 ± 7.0	0.010
VO_2peak/FFM ($ml \cdot min^{-1} \cdot kg^{-1}$)	62.7 ± 5.7	65.8 ± 5.0	58.1 ± 2.8	0.024
$V_E$peak ($l \cdot min^{-1}$)	73.1 ± 16.2	78.0 ± 19.7	65.6 ± 4.4	n.s.
HR_{peak} (bpm)	197.6 ± 5.9	197.0 ± 7.2	198.5 ± 4.1	n.s.

Note: PHV = peak height velocity, VO_2peak = peak oxygen uptake, $V_E$peak = peak ventilation, HR_{peak} = peak heart rate, bpm = beats per minute, FFM = fat free mass) and the significant differences between boys and girls (n.s. = not significant).

Figure 2 displays the hiking strap load (HSL) (in relation to HSL_{max}) throughout protocol as an expression of hiking intensity. All participants performed the hiking protocol at the given intensities. It was shown that the participants performed close to their maximal HSL at starting and finishing bout (i.e., 98.5 ± 11.2 % HSL_{max} or 224.3 ± 72.5 N). The HSL was also calculated from maximal (86.2 ± 13.3 % HSL_{max} or 196.1 ± 61.5 N), hard (71.8 ± 13.1 % HSL_{max} or 163.4 ± 60.8 N), average (31.8 ± 12.1 % HSL_{max} or 72.3 ± 56.1 N) and light hiking intensity (26.8 ± 9.2 % HSL_{max} or 61.0 ± 42.6 N). Moreover, the integrated Electromyography ($_{i}$EMG) of the right Musculus Vastus Lateralis showed a great variability throughout each bout: 76.8 ± 29.6 % MVC, 59.0 ± 25.9 % MVC, 16.2 ± 10.3 % MVC and 12.9 ± 8.7 % MVC during maximal, hard, average and light hiking respectively. In addition, no significant changes in HSL could be seen for every separate hiking intensity throughout protocol.

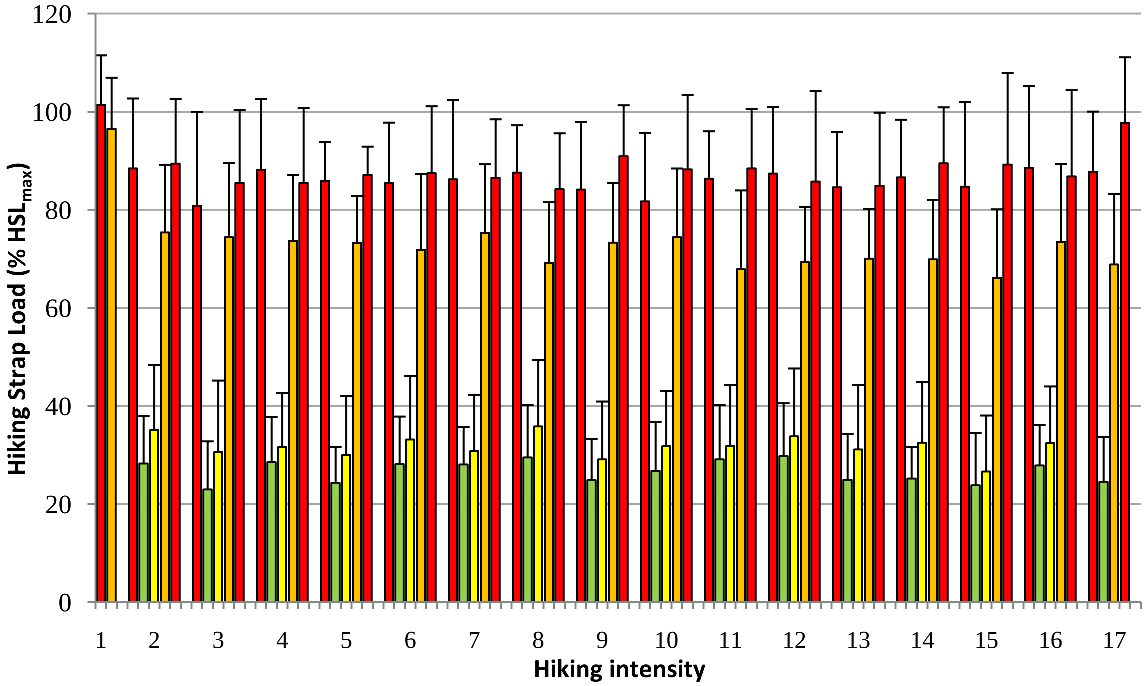

Figure 2: *Mean hiking strap load (HSL) of 10 optimist sailors. Red = maximal hiking intensity, orange = hard hiking intensity, yellow = average hiking intensity, green = light hiking intensity.*

The cardiorespiratory responses to simulated upwind sailing exercise are displayed in table 2. Oxygen uptake (VO_2) ($p < 0.01$) and Ventilation (V_E) ($p < 0.01$) increased during the UST significantly up to circa 40 % VO_2peak and 30 % $V_E$peak respectively. Respiratory Exchange Ratio (RER), however, did not change significantly throughout UST and did not exceed 1.

Also, heart rate (HR) increased significantly ($p < 0.001$) up to circa 70 % HR_{peak}. Both diastolic (DBP), systolic (SBP) and mean arterial blood pressure (MAP) increased significantly up to 95 ($p < 0.05$), 150 ($p < 0.05$) and 115 mmHg ($p < 0.01$) respectively. In addition, the rate of perceived exertion (RPE) increased significantly ($p < 0.001$) up to 16 ± 2.

***Table 2:** Physiological responses to 28 min and 20 s upwind sailing (mean ± SD) of 10 Optimist (6 male and 4 female) sailors.*

Parameters	Pre	Bout 1	Bout 5	Bout 11	Bout 15	Bout 17
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) §§		12.3 ± 2.2 ^{a}	22.2 ± 3.8 ^{b}	19.3 ± 5.9 ^{a,b}	18.3 ± 7.4 ^{a,b}	20.3 ± 4.0 ^{b}
VO_2 (% VO_2peak) §§		22.9 ± 2.4 ^{a}	42.2 ± 9.0 ^{b}	37.1 ± 12.9 ^{a,b}	34.1 ± 13.6 ^{a,b}	38.4 ± 7.3 ^{b}
V_E ($l \cdot min^{-1}$) §§		14.2 ± 5.4 ^{a}	23.3 ± 5.0 ^{b}	20.1 ± 5.8 ^{a,b}	19.6 ± 4.0 ^{b}	19.4 ± 4.2 ^{a,b}
V_E (% $V_E$peak) §§		19.4 ± 6.9 ^{a}	32.3 ± 5.7 ^{b}	27.8 ± 7.7 ^{a,b}	27.3 ± 5.0 ^{b}	27.3 ± 5.5 ^{a,b}
RER		0.89 ± 0.11	0.85 ± 0.07	0.83 ± 0.06	0.81 ± 0.05	0.85 ± 0.06
HR (bpm) §§§	85 ± 8 ^{a}		120 ± 19 ^{b}	131 ± 19 ^{b}	136 ± 17 ^{b}	136 ± 15 ^{b}
HR (% HR_{peak}) §§§	43 ± 4 ^{a}		61 ± 10 ^{b}	66 ± 10 ^{b}	69 ± 9 ^{b}	69 ± 8 ^{b}
DBP (mmHg) §	73 ± 10 ^{a}		95 ± 23 ^{a,b}	94 ± 16 ^{b}	95 ± 17 ^{b}	87 ± 17 ^{a,b}
SBP (mmHg) §	115 ± 14 ^{a}		155 ± 24 ^{b}	138 ± 10 ^{b}	135 ±30 ^{a,b}	128 ± 16 ^{a,b}
MAP (mmHg) §§	87 ± 7 ^{a}		115 ± 20 ^{b}	109 ± 14 ^{b}	108 ± 20 ^{a,b}	100 ± 11 ^{a,b}
RPE §§§			12 ± 1 ^{a}	14 ± 2 ^{b}	15 ± 2 ^{b,c}	16 ± 2 ^{c}

Note: VO_2 = oxygen uptake; V_E = ventilation; RER = respiratory exchange ratio; HR = heart rate; bpm = beats per minute; DBP = diastolic blood pressure; SBP = systolic blood pressure; MAP = mean arterial blood pressure; RPE = rate of perceived exertion) (Significant repeated measures ANOVA main-effect: § $p < 0.05$, §§ $p < 0.01$, §§§ $p < 0.001$. Post hoc pairwise differences are shown by the letters ^{a,b,c}. The same letter indicates that the parameter did not differ between the bouts. Bouts with a different letter significantly differ. $p < 0.05$ was used as the level of significance.

Figure 3 demonstrates the physiological responses of the Vastus lateralis to simulated upwind sailing exercise. Statistical analysis (repeated measures ANOVA) revealed that there was a significant main effect for Mean Power Frequency (MPF) ($p = 0.032$ and $F = 30.385$) and Root Mean Square (RMS) ($p = 0,036$ and $F = 27,235$). The post hoc analysis from MPF showed that 3 phases could be detected throughout the protocol (figure 3) : (1) a first significant MPF-decrease and RMS-increase (0 s-300 s), (2) a steady state phase in MPF and RMS (300 s-1100 s) and (3) a final significant MPF-decrease and RMS-increase (1100 s-1700 s). Figure 3c also demonstrates a significant main effect for deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) ($p = 0.002$ and $F = 595.59$). Surprisingly, post hoc analysis shows that deoxy[Hb+Mb] is stable throughout both phase 1 and 2 and shows only a significant increase during phase 3. Repeated measures ANOVA shows no significant main effect for reoxygenated hemoglobin and myoglobin (reoxy[Hb+Mb]). In addition, Figure 3e also displays a main effect for HR (p = 0.023 and F = 42.109). Post hoc analysis demonstrates a significant increase throughout phase 1 and a stabilization throughout phase 2 and 3.

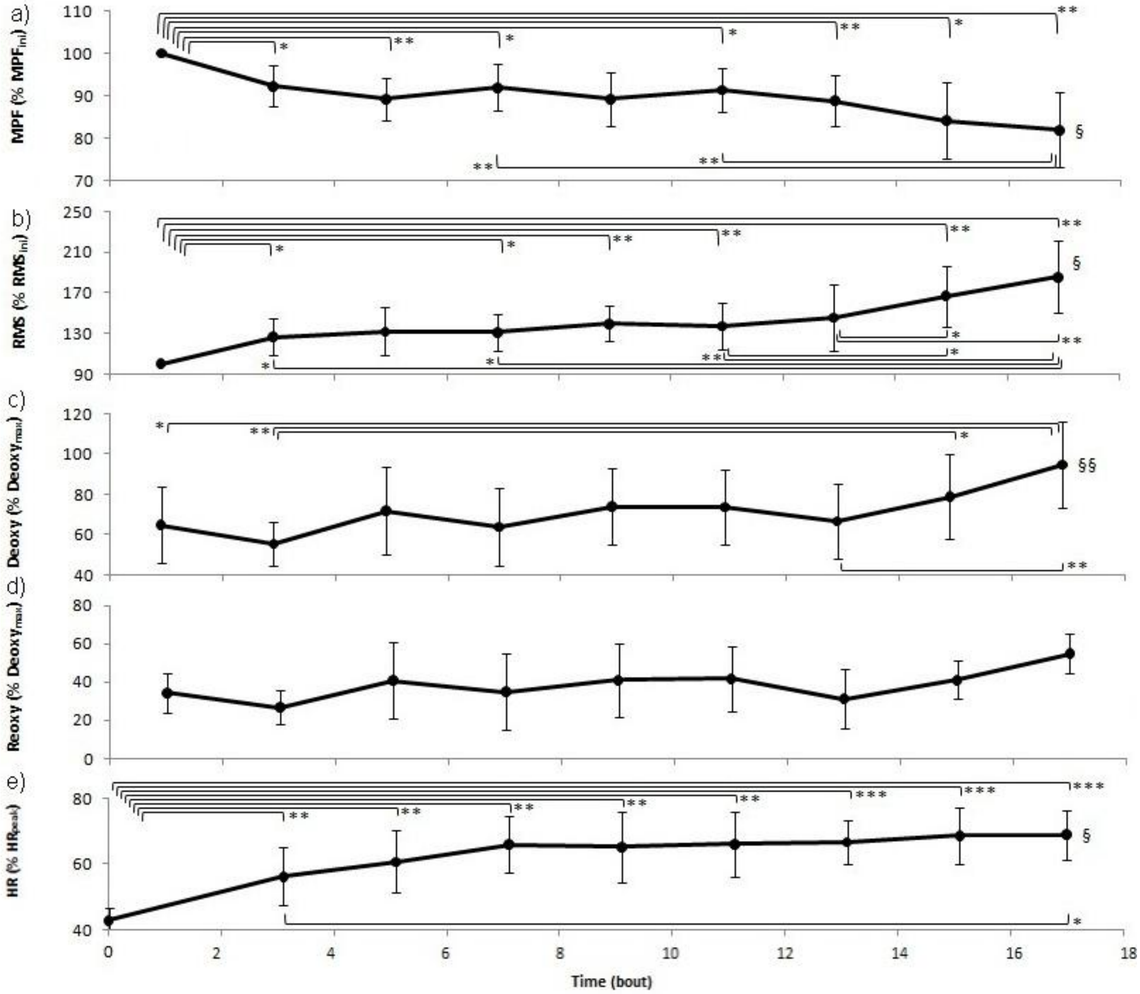

Figure 3: *Mean power frequency (MPF), root mean square (RMS), deoxygenated hemoglobin and myoglobin concentration (deoxy), reoxygenated hemoglobin and myoglobin concentration (reoxy) and heart rate (HR) responses of 10 optimist sailors during protocol. (repeated measures ANOVA main effect: § p < 0.05, §§ p < <0.01, §§§ p < 0.001; post hoc comparisons: * p < 0.05, ** p < 0.01, *** p < 0.001)*

Discussion

Although over 130.000 children are sailing the Optimist, scientific literature lacks information on the physiology of youth (Optimist) sailing. This study aimed to gain more insight into the physiological and muscular responses to simulated upwind sailing in Optimist sailors. Therefore, an Optimist ergometer and protocol were developed.

This population of Optimist sailors are well trained both on and off water. The fact that the girls show a significant lower peak power output and VO_2peak in comparison to the boys is in line with literature (Rowland et al., 2000). Nonetheless, as the Optimist class competition rules describe that boys and girls can compete together (i.e. similar to some other youth sports competitions) up to the age of 15, it is justified that this group of high level Optimist sailors consists of both boys and girls. Also, note that the dimensions of the Optimist boat (2.30m length and 1.15m width) induce an Optimist profile of 40-50 kg (Rodio et al., 1999) and ensure that early-maturing children automatically outgrow this boat and switch to an adult dinghy, by the age of 15. Also, as all responses were expressed as a percentage of their own maximum, it is acceptable to observe this group of high level male and female Optimist sailors together as one group of high-level Optimist sailors. In addition, both male and female participants show a very good functioning of the aerobic metabolism; comparable to that of male soccer players (Wong et al., 2011) and female tennis players (Petracic & Vucetic, 2008) of the same age.

The participants' hiking intensity, determined by hiking strap load (HSL), did vary as indicated by the descriptors *maximal hiking, hard hiking, average hiking, light hiking* and *tacking* (figure 2). It can be assumed that the sailors accurately performed the upwind sailing test (UST). HSL and hiking integrated Electromyography ($_i$EMG) values exceeded 100 % in some participants. This is not surprising because the maximal HSL and hiking $_i$EMG were determined isometrically which is in contrast with the quasi-isometric UST protocol. Moreover, both HSL (in % HSL_{max}) and Vastus Lateralis $_i$EMG are comparable to other literature reports of HSL (Blackburn, 1994; Mackie & Legg, 1999; Mackie et al., 1999) and $_i$EMG (Vogiatzis et al., 1993, 1996; Vangelakoudi et al., 2007). Also, Heart rate (HR), mean arterial blood pressure (MAP) and oxygen uptake (VO_2) are comparable to earlier on-water measurements (Rodio et al., 1999). Our findings seem to reflect the cardiorespiratory and muscular demands during on-water upwind sailing. The significant increases in VO_2, ventilation, HR, diastolic, systolic and MAP indicate that the cardiorespiratory responses increase only significantly in the beginning of the protocol in order to meet the increased metabolic demand. Following this increase, these cardiorespiratory variables stabilized from bout 5 to the end of the UST, despite the increasing rate of perceived exertion (RPE), suggesting that the perceived fatigue probably originates at the muscle level.

Based on Mean Power Frequency (MPF) and Root Mean Square (RMS) progress which has been argued to reflect muscle fatigue development (Coburn et al., 2005; Callewaert et al., 2013b), the muscular responses to upwind sailing (figure 3) can be divided into 3 phases: (1) a first significant increase in muscular demand (0 s-300 s), (2) a steady-state phase (300 s-1100 s) and (3) a second increase in muscular demand and onset of muscle fatigue (1100 s-1700 s). In the first phase, the maximal hiking exercise performed during starting procedure will cause an increased muscular and metabolic demand, resulting in an increased state of muscle fatigue, indicated by a decrease in MPF and an increase in RMS (Coburn et al., 2005). We assume that additional muscle fibers will be recruited in order to meet these requirements. In addition, the increased metabolic demand will also result in an elevated cardiovascular response, inducing a HR-increase and probably also an increase in muscle perfusion (Ferreira et al., 2005; Callewaert et al., 2013a). In this phase, deoxygenated hemoglobin and myoglobin (deoxy[Hb+Mb]) immediately increases in order to meet the increased muscular oxygen demand.

After the demanding starting phase, it is suggested that sailors will try to stabilize (steady-state phase) the muscular and metabolic demand. At this point, we assume that sailors adapt their intramuscular coordination pattern (i.e., between different synergistic muscles) (Maïsetti et al., 2006; Boyas et al., 2009; Watanabe & Akima, 2010; Mitchell et al., 2011; Boyas & Guével, 2011) in order to meet the muscular demand (Callewaert et al., 2013a). A second hypothesis for this stabilization in NIRS- and EMG-measurements can be attributed to the active recovery during tacking. During the tack, sailors get up and change boat side. At this point, relaxation causes a rapid outflow of deoxygenated blood that was trapped in the muscle due the increased intramuscular pressure and a rapid inflow of oxygenated blood (Callewaert et al., 2013a). According to reoxy[Hb+Mb]-results, about 30 to 40 % of the deoxy[Hb+Mb] under the probe is in this way substituted by fresh oxygenated [Hb+Mb].

As such, sailors probably benefit from the abovementioned tack- and other fore and aft body movements (or the alternate-legs-strategy) (Spurway, 2007). This technique often allows momentary relaxation (and thus recovery) of the lower limbs, in order to endure this hiking exercise for a long time (Callewaert et al., 2013a).

Despite no increase in hiking $_{i}$EMG, at a certain moment in the sailing course (i.e. at circa 20 minutes), MPF starts to decrease and RMS to increase reflecting an increased state of muscle fatigue, although this did not result in a drop of HSL. RMS-increase can indicate an additional recruitment of muscle fibers (Coburn et al., 2005). Supported by the significant increase in deoxy[Hb+Mb] during this phase, we can suggest that a great proportion of the additional muscle fiber recruitment are probably type II muscle fibers (Boone et al., 2010; Callewaert et al., 2013a). Moreover, the reoxy[Hb+Mb] increases in this third phase as well, which indicates the importance of the compensation strategies (i.e., tacking etc.) in the maintenance of this hiking exercise (Vogiatzis et al., 2008, 2011). In addition, during the final bout, this progress in MPF, RMS, deoxy[Hb+Mb] and reoxy[Hb+Mb] is even further enhanced by a greater state of metabolic and muscular demand that is required as a simulation of the struggle on water to get around the upwind buoy. In addition, it can be argued that the increase in deoxy[Hb+Mb] in bout 13-17 could be related to a reduction in microvascular oxygen availability or to changes in muscle fiber recruitment (Vogiatzis et al., 2008). For bout 17, it is possible that the oxygen availability is reduced in relation to the high intensity of the hiking exercise which might result in a restricted blood flow and thus an increased oxygen extraction. However, from bout 13 to 15, there was no change in the cardiorespiratory parameters, indicating that cardiac output presumably remained stable. Also, the study of Vogiatzis & colleagues (2001) in which Doppler ultrasound was used during three hiking actions to exhaustion, showed that blood flow velocity was not limiting.

The results at the muscle level are quite similar to our earlier findings on Quadriceps muscle fatigue in trained and untrained boys during submaximal isometric knee-extension exercise (Callewaert et al., 2013a). However, due to some methodological modifications, this study offers more insight into the mechanisms that contribute to vastus lateralis fatigue, specifically in sailing. First, the arterial occlusion preceding the protocol is of great value for the interpersonal comparability of NIRS-measurements (Van Beekvelt et al., 2001). Although earlier studies (Moalla et al., 2006; Callewaert et al., 2013a) reported that this method is very painful and rarely used in pediatric populations, we managed to use this method in this highly trained young population. Secondly, as the earlier research protocol was a pure isometric knee-extension exercise, this UST protocol resulted in quasi-isometric knee-extension exercise combined with trimming and steering exercise performed by the arms, all at constantly varying intensity, which is typical for upwind sailing (Spurway, 2007).

This study adds to the knowledge of muscle physiology in a pediatric population during a sport-specific situation. However, all participants remarked the same limitation about the UST protocol. The main difference with sailing on-water is that the boat does not move or respond to the manipulation of the sailor. Furthermore, although literature indicates a timeframe of 6 to 8s to tack (Blackburn, 1994; Legg et al., 1999), we chose 10 s to tack because of methodological constraints (wires of Oxycon and NIRS that slowed down the tacking). Also, it could be argued that the group of high-level Optimist sailors contained both boys and girls with consequently sex-induced differences. However, as the responses were all expressed as a percentage of their own maximum, it is acceptable to observe them as one group of high-level Optimist sailors. After all, they also compete together.

In conclusion, the cardiorespiratory responses (HR, VO_2 and BP) to simulated upwind sailing in this study and the results found in literature during on-water Optimist upwind sailing (Rodio et al., 1999) are comparable. Furthermore, our results at the muscular level indicate that highly trained Optimist sailors manage to stabilize the muscular demand and fatigue development during upwind sailing (after an initial increase). However, approaching the end of the hiking exercise (i.e. after approximately 20 min), the MPF-decrease, RMS-increase and deoxy[Hb+Mb]-increase possibly indicate the onset of muscle fatigue.

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Study 4:

DEVELOPMENT OF AN UPWIND SAILING ERGOMETER

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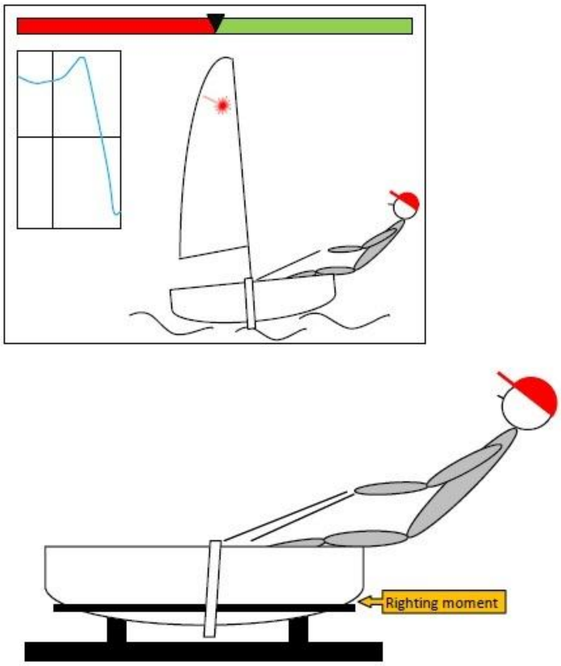

Abstract

The purpose was to develop a sailing ergometer that accurately simulates upwind sailing exercise. Therefore, a sailing ergometer that measures roll moment accompanied by biofeedback-system which allows to impose a certain quasi-isometric upwind sailing protocol (i.e. 18 bouts of 90 s hiking at constantly varying hiking intensity interspersed with 10 s to tack) was developed. Ten male high-level Laser sailors performed an incremental cycling test (ICT) (i.e. step protocol at 80W + 40W/3min) and an upwind sailing test (UST). During both, heart rate (HR), oxygen uptake (VO_2), ventilation (V_E), respiratory exchange ratio (RER) and rate of perceived exertion (RPE) were measured. During UST, also the difference between the required and produced hiking moment (HM) was calculated as error score (ES). HR, VO_2 and V_E were calculated relative to their peak values determined during ICT. After UST, the subjects were questioned about their opinion on the resemblance between this UST and real-time upwind sailing. The results showed an average HM of 89.0 ± 2.2 % HM_{max} and an average ES of 4.1 ± 1.8 % HM_{max}. Mean HR, VO_2 and V_E were respectively 80 ± 4 % HR_{peak}, 39.5 ± 4.5 % VO_2peak and 30.3 ± 3.7 % $V_E$peak. Both HM and cardiorespiratory values appear to be largely comparable to literature reports during on-water upwind sailing. Moreover, the subjects gave the upwind sailing ergometer a positive resemblance-score. These findings suggest that this ergometer accurately simulates on-water upwind sailing exercise. As such, this ergometer could be a great help in performance diagnostics and training process follow-up.

Introduction

Over the last 20 years, researchers have experienced how difficult it is to define the physiological demands of sailing upwind on dinghies (Vogiatzis et al., 1995; Maïsetti et al., 2002; Castagna et al., 2004; Tan et al., 2006; Castagna & Brisswalter, 2007; Spurway, 2007), which is characterised by a body position known as *hiking* (Blackburn, 1994; Walls et al., 1998; Tan et al., 2006; Spurway, 2007). Some studies explored the physiological demands of upwind Laser sailing on-water (Vogiatzis et al., 1995; Mackie & Legg, 1999; Mackie et al., 1999; Castagna et al., 2004; Castagna & Brisswalter, 2007) and reported on average a heart rate (HR) of 60-80 % HR_{peak}, an oxygen uptake (VO_2) of 35-45 % VO_2peak, a ventilation (V_E) of 40-50 $l \cdot min^{-1}$ and a blood lactate concentration ([La]) of 2,0-3,5 $mmol \cdot l^{-1}$ (Vogiatzis et al., 1995; Castagna et al., 2004; Castagna & Brisswalter, 2007). Other studies explored the biomechanical demands of upwind Laser sailing on-water and showed on average a mainsheet load (MSL) of 100-200 N or 25-35 % MSL_{max} with peaks up to 90 % MSL_{max} (Mackie & Legg, 1999; Mackie et al., 1999) and a hiking strap load (HSL) of 600-750 Newton (N) or 60-90 % HSL_{max} with peaks exceeding 100 % HSL_{max}. In the latter, note that HSL_{max} was determined during pure isometric hiking exercise. However, actual hiking exercise consists not only of isometric but also of eccentric knee-extension exercise (due to backward throws of the upper body). Due to these eccentric contractions, peak loads higher than 100 % HSL_{max} could be observed.

To our knowledge, several research groups have developed different sailing ergometers (Blackburn, 1994; Vogiatzis et al., 1996; Felici et al., 1999; Mackie & Legg, 1999; Maïsetti et al., 2006; Tan et al., 2006; Cunningham & Hale, 2007). However, all ergometers implemented isometric exercise. In contrast, this study seeks to impose a quasi-isometric upwind sailing protocol (i.e. an emulation) in order to accurately simulate the real upwind sailing exercise. The novelty about this upwind sailing ergometer construction is that it allows the researcher to impose a certain Quasi-isometric upwind sailing protocol (whereby the researcher defines the exact sailing conditions) (i.e. an emulation) to several subjects or to one subject at different occasions. Moreover, this ergometer enables researchers to conduct both profound physiological and biomechanical sport specific research which includes complex recordings which are not waterproof and need a careful assistance and follow-up from the researchers. Also, this ergometer allows to track error score (ES), which is the difference between the required and produced hiking moment (HM), as an indicator of hiking precision.

Importantly, note that the term *simulated* can be used in both physiological and technical circumstances. It is important to refine the nuance between the technical terms *simulation* and *emulation* from a hydro- and aerodynamic point of view. An emulation means that the ergometer imposes a certain protocol to the sailor but this protocol cannot be manipulated by the sailors movements, in contrast to a simulation. Therefore, this ergometer is (from engineering point of view) an upwind sailing emulation ergometer and not an upwind sailing simulator.

The purpose of this study was to develop a sailing ergometer that accurately simulates upwind sailing exercise by means of an upwind sailing emulation protocol. Therefore, our research group developed a Laser ergometer that measures the roll moment produced by the sailor on the boat, accompanied by a biofeedback-system that can impose a certain quasi-isometric upwind sailing protocol. Simultaneous physiological and biomechanical measurements that define this exercise were investigated and the subjects were questioned about their opinion on the resemblance between this upwind sailing test and real-time upwind sailing. It is hypothesized that this ergometer will presumably demonstrate physiological and biomechanical responses to upwind sailing exercise that are largely comparable to those reported during on-water upwind sailing. Moreover, it is thought that the sailors' feedback regarding the resemblance between the simulated and on-water sailing exercise will be positive.

Methods

Subjects

Ten male national squad youth-sailors (Laser radial), all member of the Flemish "Be Gold" talent team (± 150 sailing days/year), participated in this observational research. All subjects and their parents gave informed consent and were told that they could withdraw from the study at any time without penalty. The study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the Human Research Ethics committee of Ghent University Hospital (Ghent, Belgium). All subjects performed both an incremental cycling test (ICT) till exhaustion and an upwind sailing test (UST) within a period of 2 weeks to ensure that the level of physical fitness had not changed substantially. The subjects were asked to abstain from strenuous exercise for at least 48 h before both their visits to the laboratory.

The subjects' height (anthropometer GPM, DKSH Switzerland), body mass (Electronic SECA weighing machine) and 10 skinfolds (Harpenden skinfold caliper) were measured. Body fat percentage was calculated by the method of Parizková (Parizková, 1961). The subjects' training history (i.e. training volume, total sailing experience and Laser sailing experience) was also questioned. (table 1)

Table 1: *Subjects' anthropometry, training history and incremental cycling exercise data.*

	10 ♂ Laser sailors
Anthropometry:	
Age (years)	18.5 ± 2.0
Height (cm)	180.9 ± 4.7
Body mass (kg)	72.3 ± 4.8
Body fat percentage (%)	13.8 ± 3.0
Training history:	
Training volume (hours/week)	13.4 ± 5.1
Sailing experience (years)	9.7 ± 2.5
Laser experience (years)	2.9 ± 1.3
Incremental cycling exercise data:	
Peak Power output (Watt)	336 ± 33
VO_2peak ($ml \cdot min^{-1} \cdot kg^{-1}$)	57.1 ± 4.2
$V_E$peak ($l \cdot min^{-1}$)	143 ± 24
RER_{peak}	1.17 ± 0.04
HR_{peak} (bpm)	199 ± 9
$[La]_{peak}$ ($mmol \cdot l^{-1}$)	11.6 ± 1.5
Power output at AT_4 (Watt)	248 ± 35
VO_2 at AT_4 (% VO_2peak)	82.8 ± 5.7
HR at AT_4 (bpm)	179 ± 9

VO_2 = oxygen uptake, V_E = ventilation, RER = respiratory exchange ratio, HR = heart rate, [La] = blood lactate concentration, AT_4 = theoretical anaerobic 4 $mmol \cdot l^{-1}$ threshold, bpm = beats per minute).

Ergometer construction

The sailing ergometer consists of a rigid base frame and a section of a Laser boat. The connection between the base frame and the Laser boat allows measurement of the roll moment exerted to the boat. This is achieved with two roller bearings (in the longitudinal symmetry plane of the boat) and a force dynamometer (more information is provided below). The latter restrains the roll motion of the hull at the portside in order to measure the roll moment on the boat. Dagger board, mast and sail were removed from the boat as well as the entire section in front of the mast. Only rudder, mainsheet and hiking straps were kept on the boat. Rudder and mainsheet arrangement were attached such that a resistance is provided that matches with a Laser dinghy in winds of >15 knots (based on literature and unpublished preliminary on-water research which investigated the load on rudder and mainsheet). On the tiller, an elasticized rope provides a resistance of about 15 N (Blackburn, 1994) and a 10mm shock cord (Cunningham & Hale, 2007) was used to apply a 120 N resistance on the mainsheet (Mackie & Legg, 1999). This resistance was validated by using weight-calibration.

Experimental design

Incremental cycling test (ICT)

Each subject performed an incremental cycling exercise (i.e., step protocol) on an electromagnetically braked cycle ergometer (Excalibur Sport; Lode, Groningen, The Netherlands). The work rate increased stepwise with a rate of 40 Watt per 3 min. The actual step increase was preceded by 3 min of rest on the cycle ergometer and by 3 min of baseline cycling at 80 W (Boone et al., 2010). The instantaneous pedal rate (65-70 revolutions per minute (Boone et al., 2010) was continuously visualized on a display connected to the electromagnetic cycle ergometer, so that the subjects were informed about the cadence (rpm) throughout the exercise tests. The test was terminated when the subjects could no longer maintain the instructed pedal rate, despite strong verbal encouragement. The duration of the ICT was on average 21 ± 2 min.

Upwind sailing test (UST)

The aim was to accurately emulate an on-water upwind leg. Therefore, the development of this ergometer and upwind sailing protocol was based on literature and preliminary on-water research (unpublished data).

Before the UST, the subjects were asked to perform 3 times a 5 s maximal flat-out hiking effort (interspersed with 60 s of rest) on starboard. During these 3 maximal efforts, the roll moment created by the sailor on the boat was measured and referred to as Hiking Moment (HM). The peak HM was determined as the maximal static Hiking Moment (HM_{max}). The required HM was always calculated as a percentage of their HM_{max}.

The upwind sailing protocol consists of 18 bouts of 90 s hiking at constantly varying HM interspersed with 10 s to tack. The variance in required moment which has to be induced by the subject on the dinghy by means of hiking is a function which is a summation of two; the main function (HM_{main}) and a varying function. The main function (HM_{main}) varies constantly by means of a predefined function that consists of 5 s decreasing from peak hiking after the tack, 30 s of light hiking, 25 s of average hiking, 20 s of hard hiking and 10 s of increasing hiking up to a dynamic peak value for the hiking moment before the tack (10 s) (figure 1). This hiking intensity pattern is based on preliminary regatta time pattern analyses and is thought to represent the great hiking effort that is done each time before and after every tack in order to facilitate preparation to the tack or to increase boat speed after tacking. The lighter hiking intensity between the tacks represents the recuperation periods sailors create in order to recover and delay fatigue as a result of the high hiking effort. Also, the first and last bout are different in hiking intensity than the rest of the bouts. The first bout consists of 60 s maximal hiking and 30 s hard hiking in order to represent the great hiking effort that is done to immediately take the lead of the fleet. Equally, also the last bout consists of a higher hiking effort (i.e., 10 s maximal hiking, 30 s average hiking, 20 s hard hiking and 30 s maximal hiking) to represent the effort sailors make to fetch the mark as fast as possible.

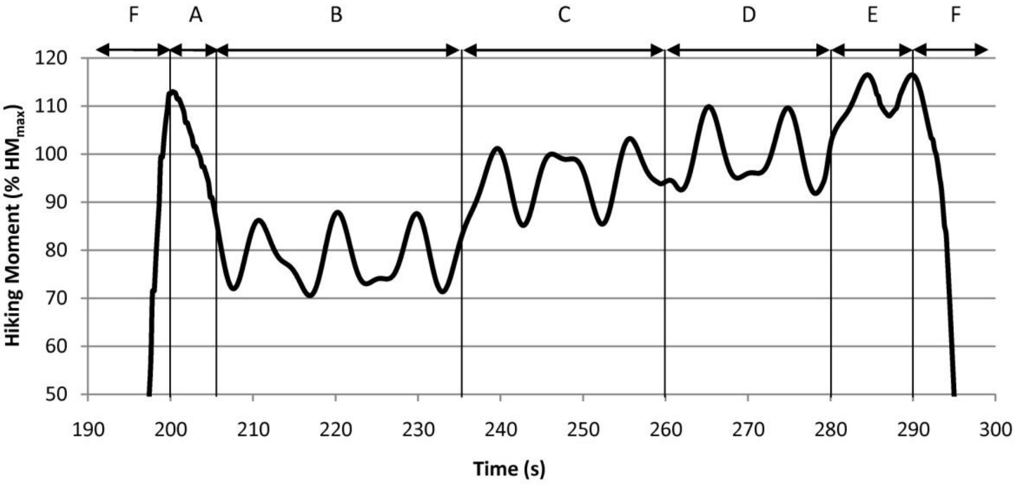

Figure 1: *Required hiking moment (HM) in time during 1 bout of an upwind sailing test: (A) 5 s decreasing from maximal HM, (B) 30 s light hiking, (C) 25 s average hiking, (D) 20 s hard hiking, (E) 10 s increasing to maximal HM, and (F) 10 s tacking.*

Throughout the protocol, a constant varying signal is added to the previously described main function in order to represent the constant changes in moment on a real Laser dinghy (due to wind shift, waves, etc.). This signal from the required hiking moment ($HM_{required}$) is described as:

$$HM_{required} = HM_{main} + \delta HM \sin\left(\frac{2\pi}{T} t\right)$$

where "δHM" indicates the amplitude of the varying function (in this case 4 % of HM_{max}) and "T" the period of the variation in seconds (4.1 s).

In order to indicate the required hiking moment ($HM_{required}$), instructions and feedback were given to the sailors by video projection on a white wall in front of them. The instruction screen consists of a biofeedback-system (A), an anticipation-system (B) and a synchronized upwind sailing video (C) (figure 2). First, a biofeedback-system indicates constantly the resultant of the $HM_{required}$ minus the HM produced by the sailor, by means of an arrow. As such, the goal for the sailor is to keep the arrow as long and as close as possible to the centre of the bi-colored beam. Second, an anticipation system indicates whether the hiking would increase or decrease (or tack). Third, also a synchronized upwind sailing video (with ambient sound) is shown in the corner of the screen in order to make the emulation more life-like. This video is assembled from regatta recordings from national Laser sailors.

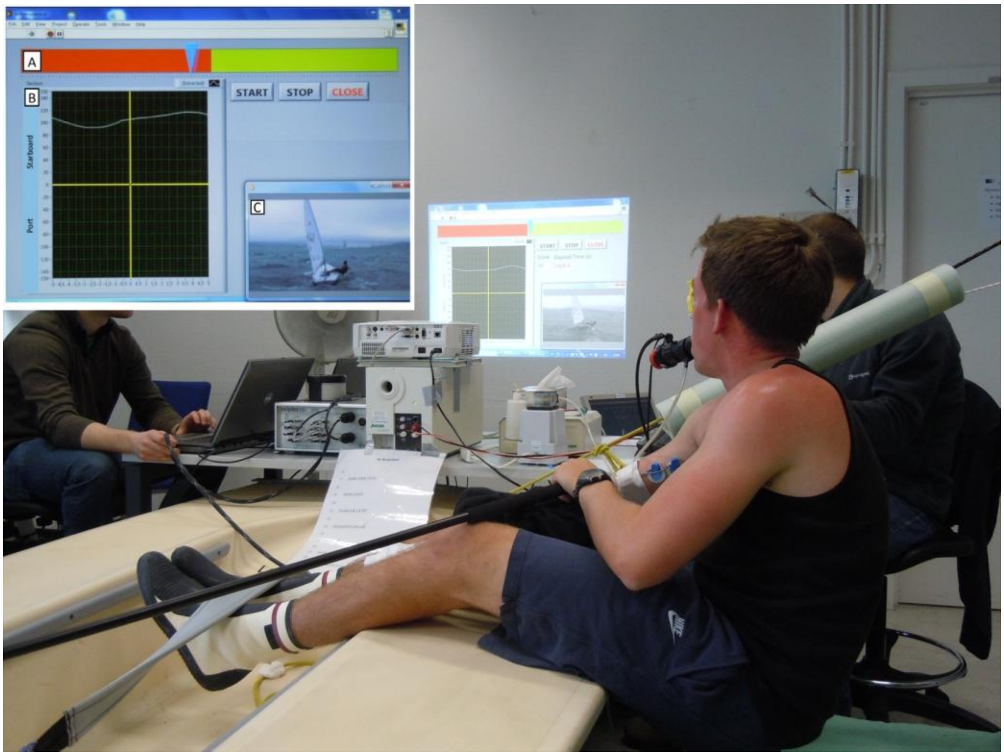

Figure 2: *Instruction screen, consisting of (A) a biofeedback system (indicates the resultant of the required hiking moment (HM) – produced HM, (B) an anticipation system (indicates whether the required HM will increase of decrease), and (C) a synchronized upwind sailing video (to make the laboratory test more lifelike). The goal for the sailor is to keep the arrow in the biofeedback system as long and as close as possible to the center of the bicolored beam.*

Measurements

During ICT, oxygen uptake (VO_2), ventilation (V_E) and respiratory exchange ratio (RER) were measured continuously on a breath-by-breath basis using a computerized O_2-CO_2 analyzer-flow meter combination and averaged during 10-s intervals (Jaeger Oxycon Pro, Höchberg, Germany) (Boone et al., 2010). Before each test, the gas analyzers and volume transducer were calibrated. Heart rate (HR) was measured with a Polar RS400 (at 5 s intervals). After each 3-minute step, including pre and post, a blood sample was taken to measure blood lactate concentration ([La]) (Analox GM7; Analox Instruments Ltd, London, UK). Peak Power output, VO_2peak, $V_E$peak, RER_{peak} and HR_{peak} were determined as the highest during an interval of 30 s (Boone et al., 2010) when at least one of the following criteria (Midgley et al., 2007) were met : VO_2 leveling off, RER > 1.10, HR > theoretical predicted maximal heart rate (220-age) ± 10 beats per minute (bpm), [La] > 8 $mmol \cdot l^{-1}$. $[La]_{peak}$ were determined for every subject as the highest value seen through protocol. For each subject, the theoretical anaerobic 4mmol·l^{-1} threshold (AT_4) was determined. Power output, VO_2 and HR at AT_4 were determined. The results from ICT are displayed in table 1.

During UST, hiking moment (HM), HR, VO_2, V_E, RER and rate of perceived exertion (RPE) were measured. The roll moment of the boat, referred to as HM, was measured through a calibrated strain gauge-type dynamometer (Burster type 8431-6010) that connected the Laser boat with the base frame. The strain gauge is connected to an amplifier (Burster type 9243) and data-acquisition hardware (National Instruments USB-6009). Logging control of the HM feedback loop to the subjects is managed through a custom Labview application. HM is recorded at 5 Herz. HR was determined at rest and at the end of each hiking bout (i.e., while the 10 s maximal hiking) by Polar RS400. Whole body VO_2, V_E and RER were measured continuously every 10 s with the Acertys Jaeger Oxycon pro. RPE was measured by 6-20 Borg-scale (Borg, 1982).

After UST, the sailors were asked to evaluate the resemblance between UST and on-water upwind sailing (Walls et al., 1998; Mackie et al., 2002). This was done by giving a score on 8 different aspects of the hiking protocol (starting procedure, hiking position, variation in hiking intensity, tacking procedure, fatigue development, boat tilt, rudder load, mainsheet load). Therefore, a Likert-scale (1 = very bad, 2 = bad, 3 = moderate, 4 = good, 5 = very good) (Mackie et al., 2002) was used. Afterwards, the researcher briefly asked the subject to motivate their opinion and noted down their remarks on the ergometer.

Data-analysis

The hiking moment (HM) is the average hiking load per bout (i.e. during each 90 s hiking period) and is expressed as a percentage of HM_{max}. Moreover, the resultant of the required HM minus the HM produced by the subject was calculated and expressed as Error Score (ES). An average ES per bout (i.e. during each 90 s hiking period) was calculated to indicate the deviation of the produced hiking intensity from the required hiking intensity per bout; when ES is positive, the HM produced by the sailor was lower than the required hiking moment. HR, VO_2 and V_E were presented as relative values to respectively their HR_{peak}, VO_2peak and $V_E$peak. HR, VO_2, V_E and RER were calculated as an average value per bout (i.e. during each 90 s hiking period).

Statistical analysis

Statistical computations were performed using SPSS software (version 18; SPSS Lead Technologies Inc., Chicago, IL, USA). All data were presented as means (from all bouts) ± SD. Repeated measures ANOVA was conducted to investigate whether significant changes in ES, HR, VO_2, V_E, RER and RPE were present throughout protocol. For HR, VO_2, V_E, RER and RPE, repeated measures analyses were conducted with the mean values from bout 1, 4, 8, 12, 16 and 18. In contrast, repeated measures analysis for ES was conducted with the values from bout 2, 4, 6, 8, 10, 12, 14 and 16. Note that bout 1 and 18 were not included only in the repeated measures analysis for ES, because this would strongly influence the result of this analysis due to a higher required HM during the first and last bout (based on preliminary research before the beginning of these experiments). When a significant main-effect was detected, one on one post hoc comparisons, followed by the Bonferroni-type adjustment, were conducted (Callewaert et al., 2013). Statistical significance for all analyses was set at $p < 0.05$.

Results

Table 1 demonstrates that the population is youthful (18.5 ± 2.0 years), but has already a great sailing experience (9.7 ± 2.5 years) and is well-trained both on and off water (respectively ± 150 sailing days/year and 13.4 ± 5.1 hours dry land training/week). Both their peak oxygen uptake (57.1 ± 4.2 $ml \cdot min^{-1} \cdot kg^{-1}$) and Maximal Power output (336 ± 33 Watt), obtained during ICT, turns out to be well developed.

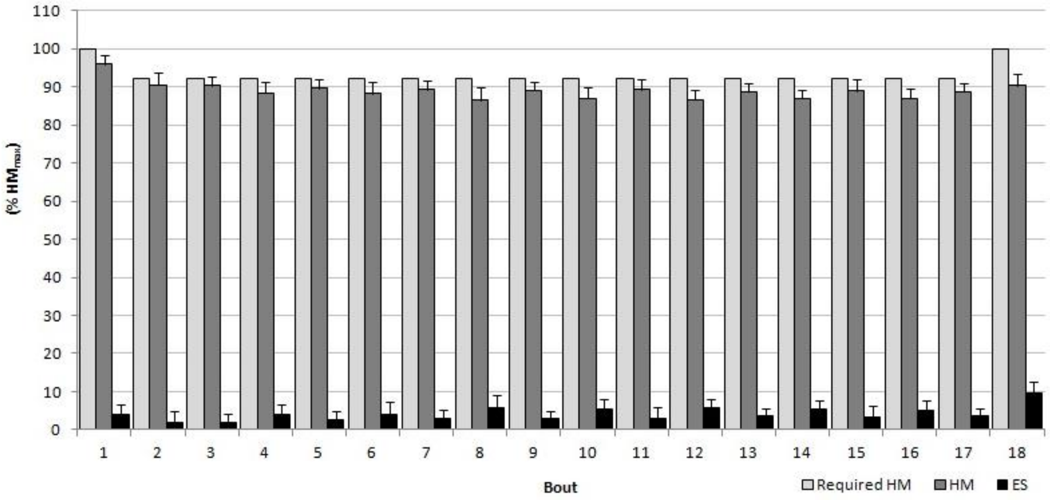

Figure 3: *Comparison of required hiking moment (HM), mean (±SD) HM produced by the sailor, and mean (±SD) error score (ES) as a result of the difference between the 2.*

Figure 3 shows the progress of both the required and the produced hiking moment (HM) and the difference between both, expressed as Error Score (ES). The Error Score (ES) is on average 4.1 ± 1.8 % HM$_{max}$ (table 2) and repeated measures ANOVA shows no significant changes in ES over time, first and last bout not included. Heart rate (HR) significantly increased throughout protocol ($p < 0.001$, $F = 16.713$). It sharply increased immediately after exercise onset and levels off very fast (i.e. only bout 1 differed significantly from bout 4, bout 8, bout 12, bout 16 and bout 18). Also, oxygen uptake (VO_2) and ventilation (V_E) significantly increased (resp. $p < 0.001$, $F = 61.073$ and $p < 0.001$, $F = 37.094$) (table 2) throughout protocol. The progress in VO_2 and V_E was comparable to that in HR: sharp increase immediately after exercise onset and very fast leveling off (i.e. only bout 1 differed significantly from bout 4, bout 8, bout 12, bout 16 and bout 18). Moreover, the rate of perceived exertion (RPE) also increased significantly throughout protocol ($p < 0.001$, $F = 72.888$). Post hoc analysis showed a significant increase up till bout 8, a leveling off till bout 16 and a significant increase from bout 16 till bout 18. In contrast, respiratory exchange ratio (RER) showed no significant change throughout protocol.

Table 2: *Mean (± SD) hiking moment (HM), Error score (ES), heart rate (HR), oxygen uptake (VO_2), ventilation (V_E), respiratory exchange ratio (RER) and rate of perceived exertion (RPE) during 18 bouts of 90 s hiking.*

Parameter	Mean (± SD)
Hiking Moment (% HM_{max})	89.0 ± 2.2
Error Score (% HM_{max})	4.1 ± 1.8
Heart Rate (% HR_{peak})	80 ± 4
VO_2 (% VO_2peak)	39.5 ± 4.5
V_E (% $V_E$peak)	30.3 ± 3.7
RER	0.92 ± 0.02
RPE	16 ± 2

The mean scores the subjects gave to indicate the resemblance between the UST and real-time upwind sailing, using a Likert-scale, demonstrated good resemblance-scores for starting procedure (4.2 ± 0.6), hiking position (4.0 ± 0.8), variation in hiking intensity (4.0 ± 0.8), rudder load (4.3 ± 0.8) and mainsheet load (4.6 ± 0.7). Moderate resemblance-score could be seen for fatigue development (3.0 ± 0.5) and tacking procedure (2.5 ± 1.0) and a bad score was reported for boat tilt (1.7 ± 0.7).

Discussion

The purpose of the present study was to develop a sailing ergometer that accurately simulates upwind sailing exercise. Therefore, our research group developed a Laser emulation ergometer that can measure the roll moment produced by the sailor on the boat, accompanied by a biofeedback-system that allows to impose a certain quasi-isometric hiking protocol. The major findings of this study indicated a great similarity between the physiological and biomechanical outcome from this upwind sailing test and the literature reports from on-water upwind sailing demand. In addition, the subjects gave the ergometer and upwind sailing protocol also a good general resemblance-score. As a consequence, it is suggested that this ergometer accurately simulates on-water upwind sailing exercise.

The construction of this ergometer creates certain benefits for sport specific physiological and biomechanical research. This ergometer allows to impose a certain quasi-isometric upwind sailing protocol (based on unpublished preliminary on-water research) in order to accurately simulate upwind sailing exercise. It is important to note that the present measuring frame is from hydro- and aerodynamic point of view an emulator and not a simulator. The advantage of this emulation ergometer is that exactly the same sailing protocol can be imposed on different sailors or on the same sailor on different occasions. Therefore, we suggest that this ergometer can be very useful as sport specific training and evaluation tool.

In order to express quantitatively how accurate the sailors performed the required hiking moment (HM), the difference between the required hiking moment and the HM produced by the sailor was calculated and expressed as Error Score (ES). It was demonstrated that the ES does not increase throughout protocol. As such, the overall average ES could be calculated as 4.1 ± 1.8 % HM_{max} (table 2). Considering comparable results in literature on isometric and isokinetic knee-extension force control variability at 60% MVC during short periods (i.e. ≤ 15 s) (Schiffman & Luchies, 2001) and taking into account that we are dealing with a man-machine-system that requires sportsmen to perform a mathematically determined hiking-protocol, we suggest that this variation is acceptable. In addition, it could be argued that ES represents hiking performance, because when hiking, the sailor tries to keep the boat as flat as possible on the water in order to improve the boat velocity.

The mean HM during each bout was 89.0 ± 2.2 % HM_{max} with peaks up to 100 % HM_{max} (table 2). This HM-percentage is comparable to the literature reports on hiking strap load (HSL) during on-water research (Mackie & Legg, 1999; Mackie et al., 1999) (table 3). Moreover, the assessment of roll moment created by the sailor on the boat, is a more correct method to assess hiking intensity than HSL. At exercise onset, an immediate increase in energy consumption was demonstrated by the sharp increase in heart rate (HR), oxygen uptake (VO_2) and ventilation (V_E). This increase was immediately followed by a stabilization in HR, VO_2 and V_E which indicates a steady state in energy consumption. Nonetheless, the mean HR (80 ± 4 % HR_{peak}), VO_2 (39.5 ± 4.5 % VO_2peak or 22.5 ± 2.6 $ml \cdot min^{-1} \cdot kg^{-1}$) and V_E (30.3 ± 3.7 % $V_E$peak or 42.8 ± 5.0 $l \cdot min^{-1}$) (table 2) measured during this upwind sailing test (UST) match the on-water research reports (Vogiatzis et al., 1995; Castagna et al., 2004; Castagna & Brisswalter, 2007) (table 3). In this context, however, it should be argued that the VO_2peak, obtained from the ICT in the present study, slightly underestimates the actual VO_2max. In our study, the ICT lasted on average 21 ± 2 min, whereas Buchfuhrer & co-workers (1983) showed that a test duration of 8-17 min is recommended to obtain the VO_2max. Therefore, it can be suggested that the VO_2, expressed in % VO_2peak, during the UST is slightly overestimated. Therefore, we suggest that this UST accurately represents both the physiology and biomechanics of on-water upwind sailing. This ergometer should be considered for on-land physical training for Laser sailors in case of impossibility of real sailing (e.g. unfavorable weather conditions) or for specific kicking training with simultaneous measures.

Table 3: Summary of literature reports from on-water measurements of average hiking strap load (HSL), heart rate (HR), oxygen uptake (VO_2) and ventilation (V_E) during on-water sailing upwind.

Ref	HSL (% HSL_{max})	HR (% HR_{peak})	VO_2 (% VO_2peak)	V_E ($l \cdot min^{-1}$)	Situation
Mackie et al., 1999	59 %, peaks to 77 %				On-water upwind sailing
Walls et al., 1998	87 %, peaks > 100 %				On-water upwind sailing
Vogiatzis et al., 1995		74 ± 11	39 ± 6		10min continuous upwind sailing
Castagna et al., 2004		69.3	42.5	49.8	30min sailing parcours
Castagna & Brisswalter, 2007		64.3	42.5	42.8	30min continuous upwind sailing

The subjects also gave their opinion on the resemblance between the UST and real-time upwind sailing on 8 different aspects of upwind sailing (table 3). Good resemblance-scores could be seen for starting procedure, hiking position, variation in hiking intensity, rudder load and mainsheet load. Fatigue development was demonstrated as a moderate representation of the fatigue experienced on-water. Seven subjects indicated that the protocol was heavier than on-water because of the more dynamical movements they make on-water. Also, 2 subjects noticed that the upwind leg in a regatta is shorter in time than during this UST. Moreover, four subjects reported that the tacking procedure was too slow compared to on-water tacking. Though, all subjects stated that it was not possible to tack exactly as on-water due to the wires from different measurement devices. Earlier research on the temporal patterns of hiking (Legg et al., 1999) demonstrated that tacking lasted 4-9s. Also, other simulation studies frequently used a tacking period of 5 s (Vangelakoudi et al., 2007; Vogiatzis et al., 2008). However, due to practical issues (i.e. safety care for the measure instruments), we chose to use a 10 s tacking period.

The results of this study suggest that this ergometer creates a good representation of on-water upwind sailing exercise. However, the absence of boat tilt was indicated as a limitation of this ergometer. Four subjects suggested that this influences the efficiency of creating a roll moment on the boat. However, elimination of this limitation can only be realized by modifying the static connection between the base frame and the boat by a set of actuators that are actively controlled in interaction with the forces exerted by the subject. This is done by converting the present measuring frame – from hydro- and aerodynamic point of view rather an emulator – to a genuine sailing simulator. Nonetheless, the subjects all reported that this way of simulating upwind sailing was a good basis to work with. In addition, note that this study only demonstrates the validity and not the reproducibility of this upwind sailing ergometer. However, in terms of future research, it is essential to study also the reproducibility of this ergometer.

In terms of practical application, an important advantage of this ergometer is that the base frame can be used for any type of dinghy. As such, this ergometer can easily be used as sport specific training and evaluation tool (i.e. to measure physical adaptation in sailing before and after training periods). The main reasons why the ergometer is equipped with a Laser dinghy is mainly because there is more literature on Laser sailing physiology and biomechanics than on any other type of dinghy and because in Flanders we have a well-organized homogeneous group of high-level youth sailors that could participate in this study.

In conclusion, the exercise created by this upwind sailing ergometer, turns out to be largely comparable to both on-water literature reports and subjective experience from the subjects. As such, it is suggested that this ergometer could be a great help as evaluation and sport specific training tool in function of performance diagnostics and follow-up of the training process.

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Study 5:

PHYSIOLOGICAL RESPONSES TO EMULATED UPWIND SAILING AND INDICATORS OF PERFORMANCE

International Journal of Sports Medicine (submitted)

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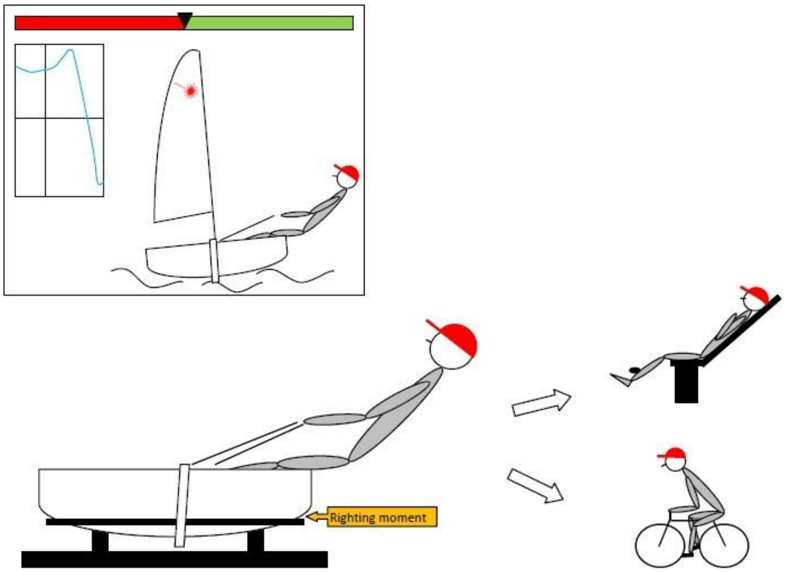

Abstract

This study investigates the cardiorespiratory, metabolic and muscular responses to an upwind sailing test (UST) on a biologically validated Laser emulation ergometer. The physiological responses (to UST) and components of the physical profile that determine those responses that are related to sailing level, were analyzed. Ten male high-level Laser sailors performed an UST, incremental cycling test (ICT) and quadriceps strength test (QST). During UST, heart rate (HR), oxygen uptake (VO_2), ventilation (V_E), respiratory exchange ratio (RER), rate of perceived exertion (RPE) and lactate concentration ([La]) were measured, combined with near-infrared spectroscopy (NIRS) and electromyography (EMG) registration of the musculus vastus lateralis. Repeated measures ANOVA showed for the cardiorespiratory and metabolic variables during UST an initial significant increase followed by a stabilization, despite a constant increase in RPE. The muscular responses demonstrated the same pattern: initial significant decrease in mean power frequency (MPF), increase in root mean square (RMS) and deoxygenated hemo- and myoglobin concentration (deoxy[Hb+Mb]), and a subsequent stagnation. Stepwise regression analysis showed that better sailing level was for 46.5 % predicted by lower MPF-decrease. Lower MPF-decrease was for 57.8 % predicted by a higher maximal isometric quadriceps strength. In conclusion, this study indicates that higher sailing level was mainly determined by a lower rate of neuromuscular fatigue during UST (as indicated by MPF-decrease). Additionally, the level of neuromuscular fatigue was mainly determined by a higher maximal isometric quadriceps strength. This might have important implications for training strategies, stressing the importance of resistance training for sailing performance.

Introduction

In Olympic Laser sailing, *hiking* is an important technique to counterbalance the tilting moment, created by the wind in the sail, in order to maintain optimal boat speed during upwind sailing (Tan et al., 2006; Spurway, 2007). Hiking is an important determinant of Laser racing performance (Legg et al., 1999; Tan et al., 2006) and is considered as a quasi-isometric exercise, mainly employing the M. vastus lateralis at a mean intensity of 30-40% maximal voluntary contraction (MVC) with peaks exceeding 100% MVC (Mackie et al., 1999; Spurway, 2007) (i.e. due to an isometric 100% MVC measurement notwithstanding a conctric and even eccentric exercise during hiking). Research on the physiological responses to hiking exercise, performed on an *isometric* sailing ergometer or dynamometer, showed that oxygen uptake (VO_2), heart rate (HR) and blood lactate concentration ([La]) increased up to 39 ± 6 % VO_2max, 74 ± 11 % HR_{max} and 2.3 ± 0.8 $mmol \cdot l^{-1}$ respectively (Vogiatzis et al., 1995). Previous studies indicated a significantly decreased musculus vastus lateralis oxygenation during hiking, indicating an imbalance between oxygen supply and demand, probably due to restricted muscle blood flow (inherent to isometric contractions > 30 % MVC) (Vogiatzis et al., 2008, 2011). Other studies, using EMG, observed a decreased mean power frequency (MPF) (as an expression of fire frequency) and an increased root mean square (RMS) (as an expression of small muscle fiber recruitment), indicating the increased rate of muscle fatigue during hiking (Maïsetti et al., 2006; Boyas et al., 2009). However, these *isometric* simulations of upwind sailing may not accurately reflect the physiological responses (i.e. the dynamics of muscle contraction and relaxation and its effect on muscle fatigue) of quasi-isometric on-water upwind sailing (Maïsetti et al., 2006; Vogiatzis et al., 2008, 2011; Boyas et al., 2009).

In our laboratory a Laser upwind sailing emulation ergometer was developed and biologically validated (Callewaert et al., 2013b). This emulation ergometer, in contrast to a simulation, makes it possible to impose a certain quasi-isometric upwind sailing protocol on the sailor without being manipulated by the sailor’s movements. This emulation ergometer also allows to impose exactly the same quasi-isometric upwind sailing protocol on different sailors (Callewaert et al., 2013b) or on one sailor on different occasions (i.e. sport-specific evaluation). The biological validity of this ergometer has been confirmed with physiological responses (i.e. on average HR, VO_2 and V_E of respectively 80 ± 4 % HR_{peak}, 39.5 ± 4.5 %

VO_2peak and 30.3 ± 3.7 % $V_E$peak) (Callewaert et al., 2013b) similar to those reported in on-water sailing studies (Vogiatzis et al., 1995; Castagna & Brisswalter, 2007).

The purpose of this study is threefold: (1) to investigate the cardiorespiratory, metabolic and muscular responses to an upwind sailing test (UST) on a biologically validated Laser emulation ergometer (Callewaert et al., 2013b), (2) to investigate whether individual sailing level (as quantified by ranking) is determined by cardiorespiratory, metabolic or muscular responses measured during UST and (3) to investigate which components of the physical profile determine those responses to UST that are related to sailing level. In line with previous studies pointing at the importance of neuromuscular fatigue during hiking exercise (Maïsetti et al., 2006; Callewaert et al., 2013a, 2014), we hypothesize that the individual sailing level is determined by MPF-decrease (as indication of neuromuscular fatigue). Furthermore, it is hypothesized that this MPF-decrease is determined by aerobic capacity and maximal isometric-eccentric quadriceps strength (Aagaard et al., 1998; Tan et al., 2006).

Methods

Subjects

Ten male national squad Laser sailors (age = 18.5 ± 2.0 years, height = 180.9 ± 4.7 cm, weight = 72.3 ± 4.8 kg and body fat percentage = 13.8 ± 3.0 %) of the Flemish *Be Gold* talent-team (± 150 sailing days per year), competing in international regattas including world championships, participated in this observational study. All subjects and their parents (if <18 years old (n=4)) gave informed consent and were told that they could withdraw from the study at any time. The study, in accordance with the declaration of Helsinki, was approved by the Human Research Ethics Committee (Ghent University Hospital, Belgium).

The subjects were ranked by the team coaches according to sailing level. Their height (anthropometer GPM, DKSH) and weight (electronic SECA) were measured. Body fat percentage was calculated from 10 skinfolds (Harpenden caliper) measurement (Parizková, 1961). Training volume was also questioned.

Experimental design

All subjects performed within 2 weeks both 2 physical profile tests (incremental cycling test (ICT) and quadriceps strength test (QST)) and an upwind sailing test (UST) and. The subjects were asked to abstain from strenuous exercise for at least 72h before visit to the lab.

Physical profile

a) Incremental cycling test (ICT)

Each subject performed an incremental progressive exercise test until exhaustion (i.e. step protocol) on an electromagnetically braked cycle ergometer (Excalibur Sport; Lode, Groningen). The test was initiated at a baseline of 80 Watt and increased every 3min with 40 Watt (Callewaert et al., 2013b). The subjects were instructed to keep pedal rate at 65-70 revolutions per minute (Callewaert et al., 2013b). The test was terminated when the instructed pedal rate could no longer be maintained, despite verbal encouragement. Gas exchange was continuously registered using a computerized O_2-CO_2 breath-by-breath metabolic measurement system (Jaeger Oxycon Pro, Germany) and were averaged in 10-s intervals (Callewaert et al., 2013b). Heart rate (HR) was measured with a Polar RS400. Pre protocol, after each 3-minute step and post protocol, a blood sample was taken to measure blood lactate concentration ([La]) (Analox GM7; Analox Instruments Ltd, London, UK).

b) Quadriceps strength test (QST)

Each subject performed an isometric and isokinetic quadriceps strength test on a Biodex dynamometer (system 2). The subjects’ leg was attached to the dynamometer arm and both hip and back were attached to the back support which was set to 120° hip-angle. Preceding each test, one familiarization-trial was conducted. During QST, the subjects were always verbally encouraged and instructed to hold their arms crossed on the chest. The QST consisted of 3 tests: (A) three 5 s maximal unilateral isometric knee extensions at 120° knee angle, interspersed with 90 s of rest, (B) 5 repetitions of unilateral concentric maximal knee extension exercise over a range of 30° to 70° knee flexion (knee extension = 0°) at $30°\cdot s^{-1}$, (C) 5 repetitions of unilateral eccentric maximal knee extension exercise over a range of 30° to 70° knee flexion at $30°\cdot s^{-1}$. All tests were interspersed with 90 s rest.

Upwind sailing test (UST)

The ergometer construction and UST protocol which emulates upwind sailing exercise in > 15 knots (based on literature and unpublished preliminary on-water research) have already extensively been described (Callewaert et al., 2013b). In short, UST consisted of 18 bouts of 90 s hiking at constantly varying hiking moment (HM) interspersed with 10 s to tack. The required HM was calculated as a percentage of their HM_{max} which was determined during flat-out hiking position. The variance in required HM was a summation of two functions: one function represents the wave motion, the other function describes the effort of the sailor in order to compensate wind fluctuations etc. The first and last bout were different than the others in order to represent the greater hiking effort that is made to immediately take the lead of the fleet and to fetch the mark as fast as possible (Callewaert et al., 2013b).

Heart rate (HR) was determined at rest and at the end of each hiking bout (i.e., while the 10 s maximal hiking) by Polar RS400. Whole body VO_2, V_E and RER were averaged in 10s-interval (Jaeger Oxycon pro, Germany) (Callewaert et al., 2013b). RPE was measured using the 6-20 Borg-scale (Borg, 1982). [La] was analyzed from capillary blood samples (Analox GM7, London) pre protocol, after bout 1, 5, 10, 15 and immediately after protocol. At muscle level, Electromyography (EMG) ('Zero wire', Aurion) from the right M. vastus lateralis was recorded at 1000 Hertz. The 34-mm-diameter Ag-AgCl EMG-electrodes (Blue Sensor, Danlee Medical Products, NY) were placed in the longitudinal axis of the NIRS-probe and each electrode site was prepared following SENIAM recommendations (Callewaert et al., 2013a, 2014). Near-infrared spectroscopy (NIRS) (Oxiplex TSTM, ISS, Champaign, Illinois) was registered at 1 Hertz (Callewaert et al., 2013a, 2014). NIRS-probe was positioned on the right M. vastus lateralis belly (10 à 12 cm above the knee) (Vogiatzis et al., 2011) and attached to the skin along the vertical axis of the thigh, secured with velcro straps and tape. Before UST protocol, an arterial occlusion was conducted on the upper leg by inflating a cuff around the thigh to 260 mmHg until the deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) leveled off. The deoxy[Hb+Mb] occlusion amplitude (i.e. the difference between the highest 10 s average of deoxy[Hb+Mb] during the occlusion and the 30 s average of deoxy[Hb+Mb] preceding the occlusion) was used as an index for maximal oxygen extraction and was set as 100 % (Callewaert et al., 2014). The subject was given 30 min of rest between arterial occlusion and UST.

Data-analysis

Physical profile

a) Incremental cycling test (ICT)

Peak oxygen uptake (VO_2peak) was determined as the highest 30 s value obtained during the test. VO_2peak was determined when the following three criteria were met: RER > 1.10, HR > theoretical predicted maximal heart rate (220-age) ± 10 beats per minute (bpm), [La] > 8 $mmol \cdot l^{-1}$ (Midgley et al., 2007). Peak power output was set as the value at exhaustion, and peak ventilation ($V_E$peak), peak respiratory exchange ratio (RER_{peak}), peak HR (HR_{peak}) and peak [La] ($[La]_{peak}$) were determined as the highest value obtained during the test (Callewaert et al., 2013b). The fixed 4$mmol \cdot l^{-1}$ lactate threshold (AT_4) was determined for every subject. [La] was set out as a function of power output, VO_2 and HR and AT_4 was determined by means of linear interpolation (Heck et al., 1985; Callewaert et al., 2013b).

b) Quadriceps strength test (QST)

The average maximal isometric (IsomQ), concentric (ConcQ) and eccentric (EccQ) quadriceps strength were calculated as an average of the left and right leg strength, since there were no significant differences between left and right isometric quadriceps strength ($p = 0.159$), concentric quadriceps strength ($p = 0.477$) and eccentric quadriceps strength ($p = 0.300$).

Upwind sailing test (UST)

HR, VO_2 and V_E were presented as percentage of HR_{peak}, VO_2peak and $V_E$peak respectively (results from ICT) and were calculated as averages from the last 10 s of each hiking bout (Callewaert et al., 2013b).

The raw EMG signal was rectified, band-pass-filtered (Butterworth filter) and integrated using MyoResearch software (MyoResearch 2.10, Noraxon, Scottsdale) (Callewaert et al., 2013a, 2014). Mean power frequency (MPF) (as expression of fire frequency and muscle fatigue development) and root mean square (RMS) (as expression of motor unit recruitment) were calculated for each bout as the mean of the final 10 s (Coburn et al., 2005; Callewaert et al., 2013a, 2014). The MPF- and RMS-values during the first bout were set to 100% and the values during the following bouts were expressed in relation to the first exercise bout (Callewaert et al., 2013a, 2014). Also, the total MPF-decrease and RMS-increase throughout the protocol were calculated as the difference between the MPF and RMS from bout 1 and 18 respectively.

The changes in deoxy[Hb+Mb] (as expression of oxygen extraction) (Boone et al., 2010; Celie et al., 2012; Callewaert et al., 2013a, 2014) during UST were expressed in relation to the deoxy[Hb+Mb] arterial occlusion amplitude (deoxy$[Hb+Mb]_{max}$) (Callewaert et al., 2014). Reoxygenation (reoxy[Hb+Mb]) was calculated immediately after each bout by setting out the amplitude of the decrease in deoxy[Hb+Mb] during the tack to the amplitude of deoxy[Hb+Mb] occlusion response (Callewaert et al., 2014).

Statistical analyses

Data were presented as mean ± standard deviation (SD) and statistical significance was set at $p < 0.05$ (SPSS 18; SPSS Lead Technologies Inc., Chicago). Normal distribution was checked for all variables. The patterns of HR, VO_2, V_E, RER, RPE, deoxy[Hb+Mb], reoxy[Hb+Mb], MPF, RMS and [La] were compared between bout 1, 5, 10, 15 and 18 by means of repeated measures ANOVA. When a significant main-effect was detected, 1-on-1 post hoc comparisons (Bonferroni) were conducted (Callewaert et al., 2013a, 2013b, 2014). Pearson correlation analysis was conducted to analyze the relation between ranking and cardiovascular (i.e. HR, VO_2, V_E, RER and RPE), metabolic (i.e. [La]) and muscular responses (i.e. MPF-decrease, RMS-increase, deoxy[Hb+Mb] at bout 18 and reoxy[Hb+Mb]) at bout 18. Subsequently, stepwise regression analysis was conducted in order to find the strongest predictor for ranking. Since MPF-decrease was the only predictor for ranking, the same method was conducted in order to identify the determinants of the MPF-decrease from the physical profile obtained from the anthropometric data, ICT and QST.

Results

The results of the incremental cycling exercise test (ICT) (already published in a previous study) (Callewaert et al., 2013b) are summarized below as these parameters were used in the correlation analysis. The mean peak power output, peak oxygen uptake (VO_2peak), peak ventilation ($V_E$peak), peak heart rate (HR_{peak}), peak lactate concentration ($[La]_{peak}$), power output at AT_4 and VO_2 at AT_4 were on average 336 ± 33 Watt, 57.1 ± 4.2 $ml \cdot min^{-1} \cdot kg^{-1}$, 143 ± 24 $l \cdot min^{-1}$, 199 ± 9 $beats \cdot min^{-1}$, 11.6 ± 1.5 $mmol \cdot l^{-1}$, 248 ± 35 Watt and 82.8 ± 5.7 % VO_2peak respectively. Quadriceps strength test (QST) showed on average 280.9 ± 49.2 N·m maximal isometric quadriceps strength, 255.2 ± 43.3 N·m maximal concentric quadriceps strength and 294.8 ± 56.3 N·m eccentric quadriceps strength.

During the upwind sailing test (UST), a significant main effect for heart rate (HR) ($p < 0.001$, F = 29.539), oxygen uptake (VO_2) ($p = 0.002$, F = 8.483) and ventilation (V_E) ($p = 0.033$, F = 4.192) was shown (figure 1). HR, VO_2 and V_E all indicated a significant initial increase and then stabilized till the end of protocol. Respiratory exchange ratio (RER) showed no significant main effect. Rate of perceived exertion (RPE) demonstrated a significant main effect ($p < 0.001$, F = 90.912) and increased continuously up to 18.5 ± 0.8 (at bout 18). Blood lactate concentration ([La]) increased significantly throughout protocol ($p < 0.001$, F = 19.593) from 2.12 ± 0.44 $mmol \cdot l^{-1}$ (pre protocol) to 4.05 ± 1.05 $mmol \cdot l^{-1}$ (at bout 1) and 6.16 ± 1.73 $mmol \cdot l^{-1}$ (at bout 18) (figure 2).

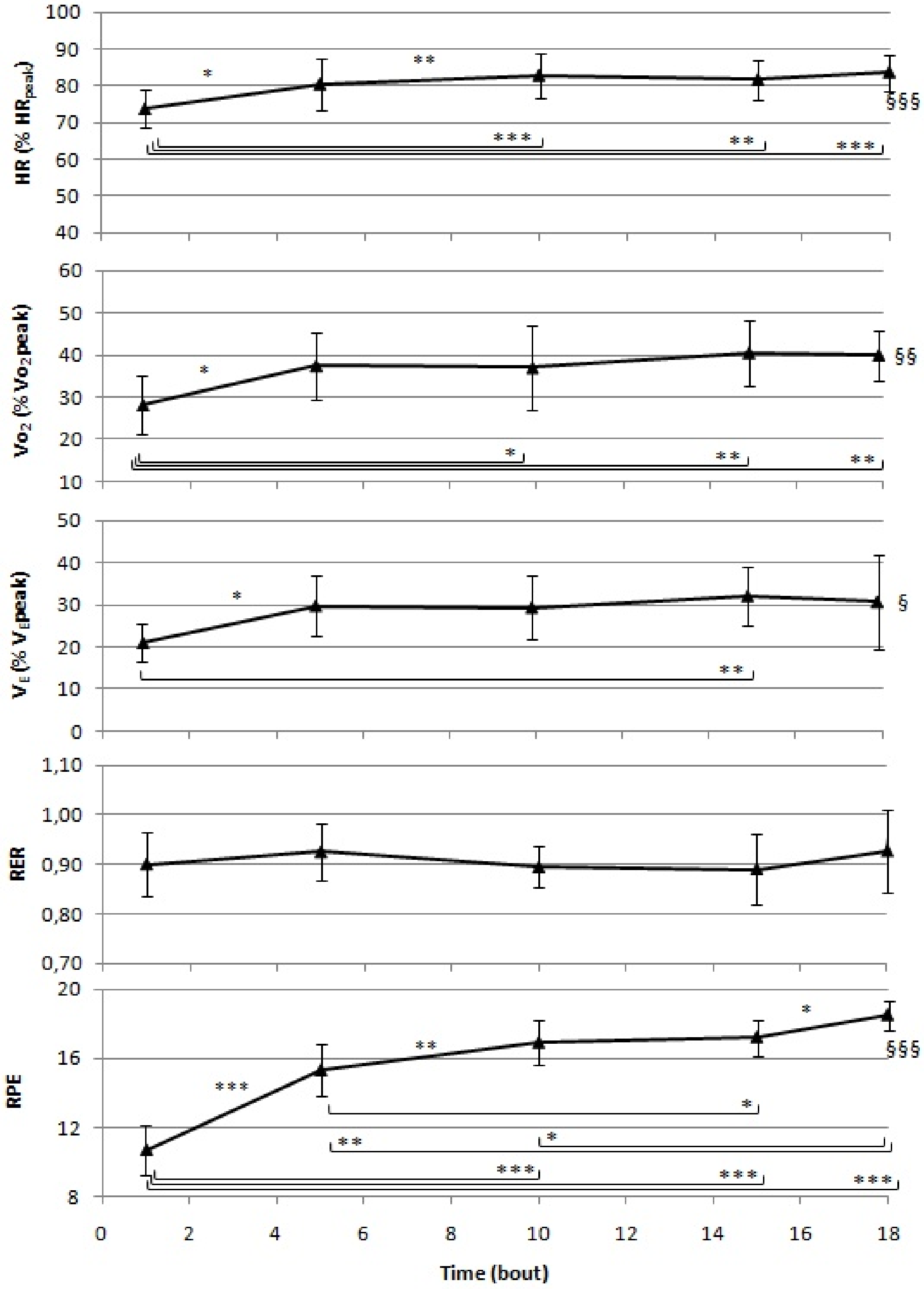

Figure 1: *Heart rate (HR), oxygen uptake (VO$_2$), ventilation (V$_E$), respiratory exchange ratio (RER) and rate of perceived exertion (RPE) progress in time. (Repeated measures ANOVA: significant main-effect: § $p < 0.05$, §§ $p < 0.01$, §§§ $p < 0.001$. Post hoc: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)*

At the muscle level, mean power frequency (MPF), root mean square (RMS), deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]) and reoxygenated [Hb+Mb] (reoxy[Hb+Mb]) responses throughout protocol (figure 2) significantly demonstrate 2 phases: (1) first significant MPF-decrease and RMS- and deoxy[Hb+Mb]-increase (0 s-500 s) and subsequently (2) a steady-state in MPF, RMS and deoxy[Hb+Mb] (500 s-1800 s). Reoxy[Hb+Mb] showed no significant main-effect ($p = 0.927$). It could be argued that there is probably a third phase at the end of protocol (i.e. second MPF-decrease and RMS- and deoxy[Hb+Mb]-increase) (i.e. 1500 s-1800 s), however this decrease was not significant.

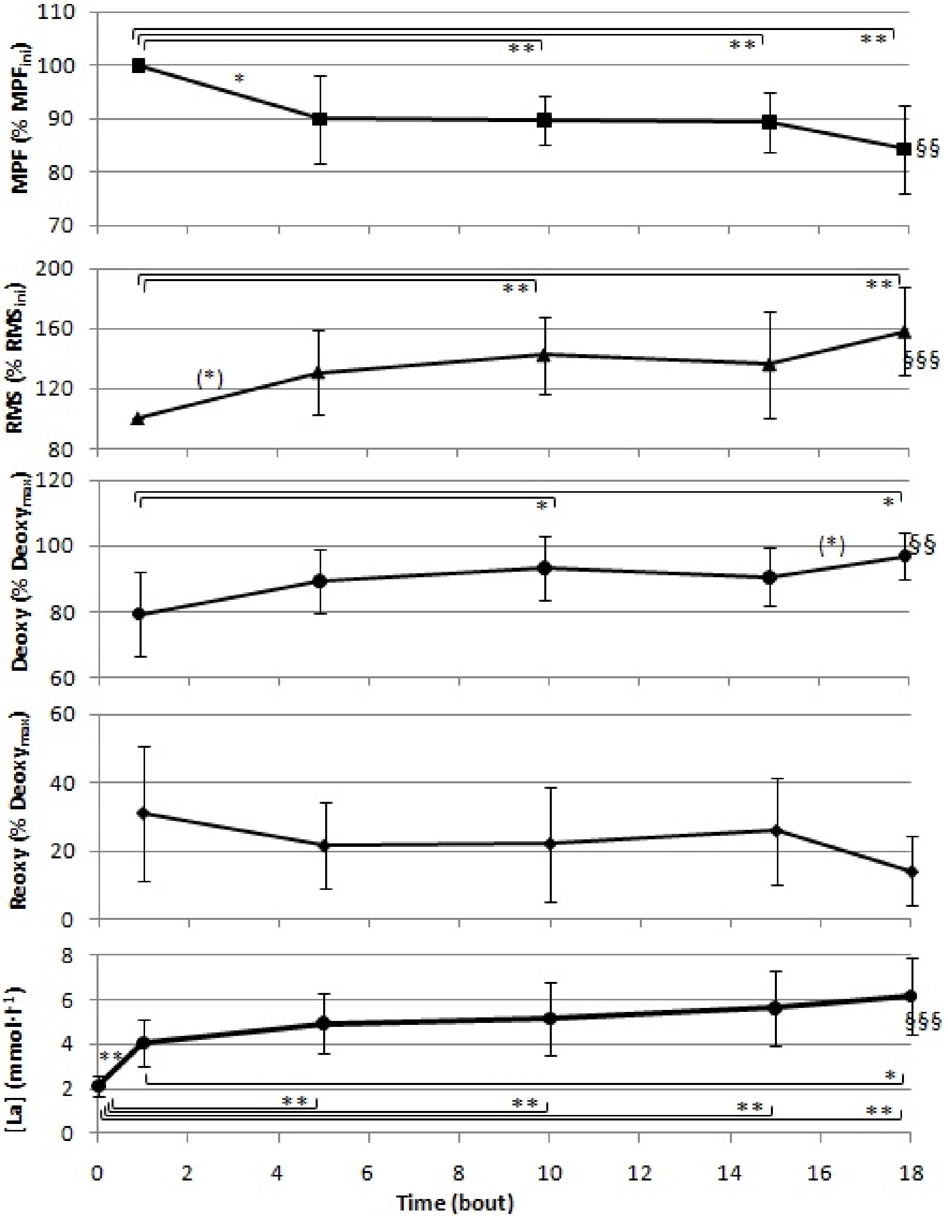

Figure 2: *Mean power frequency (MPF), root mean square (RMS), deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb]), reoxygenated [Hb+Mb] (reoxy[Hb+Mb]) and blood lactate concentration ([La]) progress in time. (Repeated measures ANOVA: significant main-effect: § $p < 0.05$, §§ $p < 0.01$, §§§ $p < 0.001$. Post hoc: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)*

Pearson correlation analysis indicated that ranking was only related to MPF-decrease (table 1). Multiple regression analysis showed that 46.5 % of the variance in ranking was predicted by MPF-decrease (p = 0.018 and adjusted $R^2 = 0.465$).

Table 1: *Pearson R correlation coefficient between ranking and the physiological responses to UST.*

UST-Parameter	Ranking	
	Pearson R	p
HR (% HR_{peak}) at bout 18	n.s.	0.373
VO_2 (% VO_2peak) at bout 18	n.s.	0.641
V_E (% $V_E$peak) at bout 18	n.s.	0.576
RER at bout 18	n.s.	0.906
RPE at bout 18	n.s.	0.591
[La] at bout 18	n.s.	0.098
MPF-decrease (% MPF_{ini})	0.724 *	0.018
RMS-increase (% RMS_{ini})	n.s.	0.208
deoxy[Hb+Mb] at bout 18	n.s.	0.838
reoxy [Hb+Mb] at bout 18	n.s.	0.965

Note: MPF = mean power frequency, RMS = root mean square, VO_2peak = peak oxygen uptake, [La] = blood lactate concentration, AT_4 = fixed 4 mmol·l^{-1} lactate threshold, Q = Quadriceps, RPE = rate of perceived exertion, deoxy[Hb+Mb] = deoxygenated hemo- and myoglobin concentration, reoxy[Hb+Mb = reoxygenated hemo- and myoglobin.($p < 0.05$)*

Furthermore, MPF-decrease was negatively related to both body weight, maximal isometric (IsomQ) and concentric quadriceps strength (ConcQ) (table 2), with IsomQ as the strongest predictor of MPF-decrease (p = 0.006 and adjusted R^2 = 0.578) (because of multicolinearity between body weight, IsomQ and ConcQ).

Table 2: *Pearson R correlation coefficient between MPF-decrease and physical profile parameters.*

Parameter	MPF-decrease	
	Pearson R	p
Training volume (hours/week)	n.s.	0.758
Height (cm)	n.s.	0.597
Weight (kg)	-0.750 *	0.012
Peak power output (Watt)	n.s.	0.162
VO_2peak (ml·min^{-1}·kg^{-1})	n.s.	0.876
$V_E$peak (l·min^{-1})	n.s.	0.268
HR_{peak} (beats·min^{-1})	n.s.	0.169
$[La]_{peak}$ (mmol·l^{-1})	n.s.	0.717
Power output at AT_4 (Watt)	n.s.	0.141
VO_2 at AT_4 (ml·min^{-1}·kg^{-1})	n.s.	0.752
Isometric Q strength (Nm)	-0.791**	0.006
Concentric Q strength (Nm)	-0.715 *	0.020
Eccentric Q strength (Nm)	n.s.	0.052

Note: *MPF = mean power frequency, VO_2peak = peak oxygen uptake, $V_E$peak = peak ventilation, [La] = blood lactate concentration, AT_4 = fixed 4 mmol·l^{-1} lactate threshold, Q = Quadriceps. (* $p < 0.05$ ** $p < 0.01$)*

Discussion

This study offers new insight into the physiology of hiking. A biologically validated emulation laser ergometer makes it possible to impose a certain quasi-isometric upwind sailing protocol on the sailor, without being manipulated by the sailor's movements (in contrast to a simulation). As such, the main advantage of this ergometer is that it allows to imitate exactly the same quasi-isometric on-water upwind leg on different sailors or on one sailor on different occasions (i.e. sport-specific evaluation) (Callewaert et al., 2013b). Moreover, this ergometer allows us to get an integrated view on the physiology of hiking by combining the registration of cardiorespiratory, metabolic and muscular responses (which is not possible on the water due to practical limitation). Note that this study was performed in highly trained sailors, practicing 13.4 ± 5.1 hours (of sailing and dry-land training) per week. Peak oxygen uptake (VO_2peak) was comparable to that of other elite Laser sailors (Castagna & Brisswalter, 2007; Bojsen-Møller et al., 2007; Cunningham & Hale, 2007) and isometric, concentric and eccentric quadriceps strength were only slightly lower compared to that of Olympic Laser sailors (Bojsen-Møller et al., 2007).

During the upwind sailing test (UST), both cardiorespiratory (i.e. heart rate (HR), oxygen uptake (VO_2) and ventilation (V_E)), metabolic (i.e. [La]) and muscular (i.e. mean power frequency (MPF), root mean square (RMS) and deoxygenated hemoglobin and myoglobin concentration (deoxy[Hb+Mb])) parameters show 2 distinct phases. A significant initial increase in HR, VO_2, V_E, [La], deoxy[Hb+Mb], RMS (as expression of motor unit recruitment) with a concomitant decrease in MPF (as expression of fire frequency) is present in order to meet metabolic demand. After this initial response, all (cardiorespiratory, metabolic and muscular) parameters show a steady-state phase (Coburn et al., 2005). It is suggested that after the demanding starting phase (i.e. bout 1), sailors will try to stabilize the muscular and metabolic demand by using recovery strategies. It is thought that sailors can adapt their intermuscular coordination pattern (Maïsetti et al., 2006; Boyas et al., 2009) and oxygen extraction pattern (Vogiatzis et al., 2008) due to active recovery strategies (i.e. tacking, fore and aft body movements or alternate-legs-strategy) (Spurway et al., 2007; Boyas & Guével, 2011; Callewaert et al., 2014). This study indicates that during these recovery strategies intramuscular pressure which causes deoxygenated-blood-pooling in the muscle, is decreased causing a rapid outflow of deoxygenated blood and inflow of oxygenated blood

(Boyas & Guével, 2011). Our results indicate that during each tack 24.9 ± 12.8 % of deoxy[Hb+Mb]$_{max}$ is substituted by oxygenated [Hb+Mb]. Though, we need to criticize that this 10 s tacking procedure is probably somewhat too slow compared with on-water tacking (4-9 s) (Legg et al., 1999; Callewaert et al., 2013b). However, due to practical issues (i.e. safety care for the measurement instruments), a 10 s tacking period was designated (Callewaert et al., 2013b). Despite the stabilization phase in both cardiorespiratory (HR, VO_2 and V_E) and metabolic ([La]) variables, a constant increase in rate of perceived exertion (RPE) is noticed. This suggests that the increase in perceived fatigue throughout the end of the protocol (i.e. between bout 15 and 18) probably originates at the neuromuscular level (Lagally et al., 2002; Callewaert et al., 2013a, 2014). Although not significant, visual inspection shows a second decrease in MPF and increase in RMS, accompanied by an increase in deoxy[Hb+Mb] between bout 15 and 18, suggesting an increased state of neuromuscular fatigue (figure 2). The increased state of muscle fiber recruitment with a concomitant increased state of deoxygenated blood suggests an induced fast-twitch muscle fiber recruitment with a different oxygen extraction pattern towards the end of the hiking protocol (Boone et al., 2010; Callewaert et al., 2013a, 2014).

Another main finding was that better sailing level is strongly determined (for 46.5 %) by a lower occurrence of neuromuscular fatigue (as quantified by MPF-decrease). Therefore, the physical profile parameters related to neuromuscular fatigue (i.e. MPF-decrease) during UST were identified. Our results showed that MPF-decrease was highly related to body weight, maximal isometric (IsomQ) and concentric quadriceps strength (ConcQ). In contrast to our hypothesis, aerobic endurance (i.e. VO_2peak, peak power output) was not related to the appearance of neuromuscular fatigue. This probably could be due to the homogeneous level of aerobic fitness (as reflected by small standard deviation in VO_2peak). As hypothesized, neuromuscular fatigue (as indicated by MPF-decrease) was mainly determined (for 57.8 %) by IsomQ. Of course, sailors with a higher maximal strength capacity need to address a lower percentage of their strength capacity compared to sailors with a lower strength capacity (Burnett et al., 2012), because in real-life the wind force is more or less equal for everyone. However, in the present study, this issue was eliminated by setting the UST in relation to the own maximal hiking moment. In comparison to previous studies which considered that the hiking performance depends in part on maximal isometric-eccentric knee extensor strength (Aagaard et al., 1998; Tan et al., 2006), this study agrees on the importance of maximal isometric quadriceps strength regarding the rate of neuromuscular fatigue. However, the importance of eccentric quadriceps strength was not confirmed here.

In conclusion, this study indicates that Laser sailors try to stabilize the metabolic and muscular cost by adapting the intermuscular coordination pattern and muscular oxygen extraction pattern by means of active recovery strategies. Further, a higher sailing level was mainly determined by a lower rate of muscle fatigue during UST and a lower rate of muscle fatigue during UST was mainly determined by a higher maximal isometric quadriceps strength during QST. These findings might have important implications for training strategies, stressing the importance of resistance training for sailing performance.

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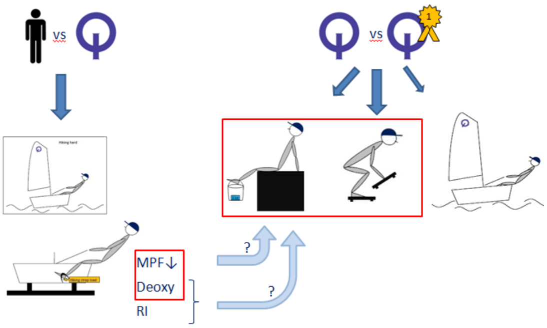
PART 3:

GENERAL DISCUSSION



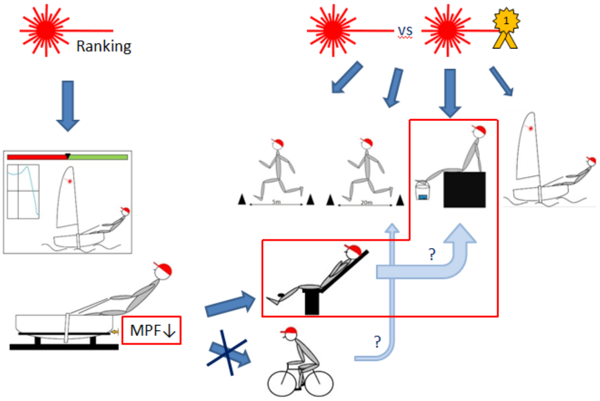


TABLE OF CONTENTS:

The general purpose of this dissertation was to establish an integrated view on dinghy sailing performance. This final chapter provides an overview of the key findings within each of the studies overarching the three research aims that were identified in the introduction, that is: (1) investigating the determinants of dinghy sailing performance, (2) developing a sailing ergometer that accurately represents the physiological responses during on-water upwind sailing, and (3) exploring the physiological mechanisms during submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing) with a distinct focus on the muscle level. Finally, conceptual and methodological reflections are provided in an attempt to advance both research and practice. In addition to these reflections, strengths and limitations across studies are also discussed.

1. Determinants of dinghy sailing performance

The table below illustrates the main findings regarding the determinants of dinghy sailing performance (table 1). Several types of studies have been conducted to contribute to our understanding on the determinants of sailing performance. On the one hand, a field study was conducted to examine the physical characteristics of dinghy sailors. These characteristics differ and discriminate between non-elite and elite Optimist and adolescent sailors. The aim is to elucidate the physical determinants of sailing performance for youth sailors (study 1). On the other hand, also a laboratory studies (study 5) added more argumentation to the solid findings of study 1.

Table 1: *Overview of significant differences, discriminating factors and predictors of dinghy sailing performance.*

	Optimist sailors	Laser sailors
Practice (study 1)	NE < E	NE < E
Motor coordination skills (study 1)	NE < E CC: 100.0 %	
Speed agility (study 1)		NE < E
Maximal aerobic endurance (study 1)		NE < E
Incremental knee extension SE (study 1)	NE < E	NE < E CC: 88.9 %
IsomQ (study 5)		**IsomQ** → 57.8 % fatigue Fatigue → 46.5 % of ranking

Note: CC = classification coefficient: … % of the elites can be correctly classified (discriminant analysis)
-> means that … determines ... % of the variance in …(multiple regression)
NE = non-elite, E = elite, SE = strength endurance, IsomQ = maximal isometric quadriceps strength

The fact that both Optimist and Laser sailors indicate significantly different practice time between elites and non-elites is not surprising (study 1). One could assume this is a consequence rather than a cause of their sailing level. The second significant difference is a higher incremental knee extension strength endurance (reflected by the bucket test) in elite Optimist and Laser sailors (study 1). This is in line with the study of Blackburn and Hubinger (1995), but in contrast to the study of Tan and co-workers (2006) who observed no significant relation between ranking and the bucket test, whereas a strong correlation was found between ranking and the maximal hiking moment over 3 min (i.e. HM_{180}) ($r = 0.62$; $p < 0.05$). Similarly, no correlation between ranking and hiking endurance on a Laser simulator was observed in the study of Vangelakoudi (2007), whereas a positive correlation

($r = 0.62$; $p < 0.05$) between ranking and the time to exhaustion during an isometric knee extension strength endurance exercise on an isokinetic dynamometer (at 45 % MVC) was observed. Considering these literature reports and the results of this research, it can be suggested that knee extension strength endurance is of significant importance for sailing performance in both Optimist and Laser sailors (study 1). Furthermore, the bucket test appears to be a discriminating factor between non-elite and elite Laser sailors, classifying 88.9 % of the elites in the correct group (study 1). Moreover, the laboratory study in Laser sailors (study 5) confirms the importance of incorporating the development of maximum strength in training programs at young age (> 14 years), as already suggested by Aagaard & co-workers (1998) and Tan & colleagues (2006). A straightforward relation between ranking and maximal strength is absent in a prepubertal population due to fact that anaerobic metabolism is influenced by maturation (Eriksson et al., 1973). Yet, several studies showed an effect of strength training for prepubertal children (Blimkie, 1993; Ozmun et al., 1994). However, prepubertal children are in the crucial phase to develop motor coordination skills. Accordingly, the motor coordination skill development is presumably more indicative for elite performance in this age group.

Motor coordination skills appeared to be significantly different between elite and non-elite Optimist sailors (study 1). Moreover, motor coordination (as reflected by side step and side jump score on the KTK test) can discriminate the elite from the non-elite Optimist sailors, classifying the elite Optimist sailors for 100 % in the correct group. This result might suggest that (strength- and speed-oriented) motor coordination skill is an important indicator of Optimist sailing performance (study 1). These findings underline the role of motor coordination throughout the development of a future elite athlete. This is in line with the suggestions in other sports which show that elite young athletes have a significantly better motor coordination than non-elites (Paillard et al., 2011; Vandorpe et al., 2011).

For Laser sailors, there are 2 additional parameters which are significantly different between elite and non-elite Laser sailors. Speed agility (i.e. reflected by the 5m shuttle run score) is probably important in terms of fast and accurate boat handling skills, and maximal aerobic endurance (as reflected by 20m shuttle run score) is presumably important in terms of fast recovery between and after the different races. It should be mentioned that regattas consist of different races per day and sometimes even 10 days in a row (ISAF, 2012).

Maximal aerobic endurance is also considered to be important to manage the high training and racing load. Each training or racing day consists of several hours (more than 3, up to 6 to 8 hours) on the water, almost constantly sailing at different intensities.

To conclude, the findings related to the determinants of sailing performance are summarized in the model below. The model clearly demonstrates the importance of practice, incremental knee extension strength endurance and motor coordination skills for Optimist sailing performance and the importance of practice, speed agility, maximal aerobic endurance and incremental knee extension strength endurance for Laser sailing performance. Moreover, the model also emphasizes that motor coordination skills for Optimist sailors and incremental knee extension strength endurance for Laser sailors are characteristics indicating whether a sailor is an elite or a non-elite sailor. This suggests the fundamental importance of incorporating motor coordination skill training for Optimist sailors and strength training for Laser sailors.

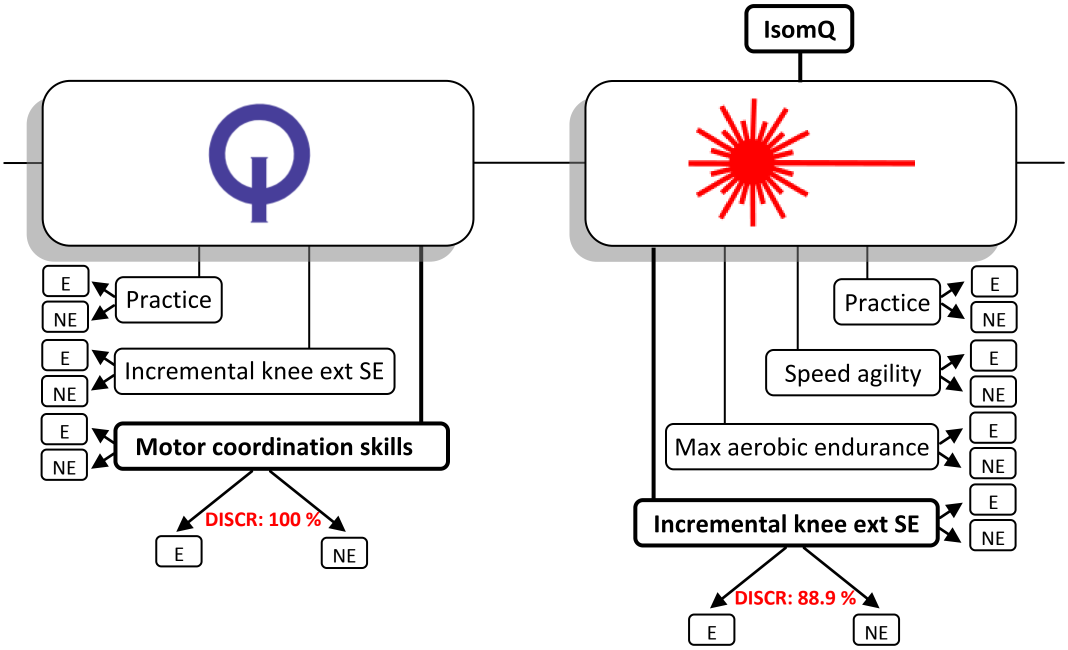


Figure 1: *Overview of significant differences, discriminating factors (DISCR) and related factors to dinghy sailing performance in Optimist and Laser sailors. (Ϙ = Optimist sailors, ✶- = Laser sailors, E = elite, NE = non-elite, SE = strength endurance, IsomQ = maximal isometric quadriceps strength)*

2. Innovation in sailing ergometers:

Several types of sailing ergometers exist: ergometers aiming to evaluate sailing technique and tactics (Walls et al., 1998; Mulder & Verlinden, 2013) and ergometers aiming to represent the physiological responses during on-water (upwind) sailing or hiking.

***Table 2:** Overview of the ergometers developed to represent the physiology of (upwind) sailing or hiking.*

	Goal: to assess	Construction:	Protocol:	Assessment:
Blackburn, 1994	physiological demand of **simulated on-water sailing**	A Laser hull was supported by a wooden cradle which heeled 5° during reaching and 10° during upwind sailing MSL upwind = 98 N static, 549 N dyn MSL reaching = 59 N static, 294 N dyn Tiller load = 15 N **Static ergometer**	Simulating their normal on-water movement in tandem with video taken in winds of > 12 knots (i.e. **mimicking**) Time: 90 min = 3 x 20 min upwind & 2 x 12 min reaching according to triangle course **Quasi-static unmanaged protocol**	RM & HSL
Felici et al., 1999	Physiological demand of **submaximal knee extension to exhaustion**	Modified Harken (Italy) ergometer (0° heeling) **Static ergometer**	**Sustained static hiking** at 85% or 60 % maximal hiking torque (MHT) MHT = fully outstretched posture	RM
Cunningham & Hale, 2007	physiological and motor-skill responses to the demand of **hiking (i.e. position task)**	A Laser deck pivoted between 2 "A"-support frames and moved freely about 30° in the roll axis. A moveable, weight stack on the leeward side of the boat created a heeling moment. Trimming and sheeting was simulated **Quasi-static ergometer**	Sailors have to **balance the heeling moment**, keeping the boat horizontal. Time: 30 min Every 30 s wind gusts (duration: 10 s) Every 30 s wind lulls (duration: 5 s) Every 3, 2 or 1 min tacking Every 10 s trimming **Quasi-static unmanaged protocol**	RM
Vogiatzis et al., 1996; 2008; 2011	Physiological demand of **submaximal hiking (i.e. position task)**	By applying a constant load to the opposite side of the deck and using a spring damper mechanism, the simulator was made to pivot. Trimming was also simulated **Static ergometer**	Sailors have to hike (i.e. **balancing the heeling moment**) 5 times 3 min at 30-40 % HSL_{max} (with 5 or 15 s recovery in between) **Static unmanaged protocol**	HSL
Maïsetti et al., 2006 Boyas et al., 2009	Physiological demand of **submaximal hiking to exhaustion**	A Laser hull was supported by a wooden cradle which heeled 10° MSL was < 40 N Tiller load were applied **Static ergometer**	Sailors have to **mimic** the hiking positions on the screen and keep the hiking torque (HT) at 50 % MHT **Quasi-static unmanaged protocol**	RM
Study 3	Physiological responses to **upwind sailing exercise**	Optimist hull supported by a vast undercarriage in rigid & horizontal way **Static ergometer**	Sailors have to mimic the video at the intensity indicated in the video **Quasi-static unmanaged protocol**	HSL
Study 4 & 5	Physiological responses to **emulated upwind sailing**	The ergometer consists of a rigid base frame and a section of a Laser boat. The connection between the base frame and the boat allows measurement of the roll moment exerted to the boat **Static ergometer**	Sailors constantly have to react and anticipate the imposed hiking intensity (or tacking exercise) by means of a biofeedback system **Quasi-static managed & emulated protocol**	RM

Note: RM = uprighting moment, HSL = hiking strap load, MSL = mainsheet load, MHT = maximal hiking torque, dyn = dynamic.

The table above provides an overview of the ergometers used in studies that report physiological responses during simulated dinghy sailing (table 2). Every ergometer has its strengths and its limitations.

Our second aim was to develop a sailing ergometer that accurately represents on-water upwind sailing exercise. Firstly, a standardized submaximal isometric knee extension protocol was used to compare sailors with non-sailors (study 2). This study was of significant value in exploring for the first time the muscular mechanisms in a sailing-specific knee extension exercise (as a part of hiking) for the first time. However, the upwind sailing exercise comprises more than only the knee extension part and is certainly not performed in a standardized situation. Therefore, two versions of sailing ergometers were developed. The first attempt was to develop an Optimist ergometer (study 3). However, the disadvantage of this ergometer was that the researcher was not in control of the hiking intensity performed by the sailors during protocol. One could only check afterwards whether they performed the protocol as required or not. Therefore, a second version was developed: an emulation ergometer which made it possible to impose a certain quasi-isometric upwind sailing condition onto the sailor, without being manipulated by the sailor’s movements (in contrast to a simulation). The main advantage of this ergometer is that it allows imposing exactly the same quasi-isometric on-water upwind leg on different sailors or on one sailor on different occasions. This creates an optimal tool for sport-specific training evaluation and follow-up.

Comparing the emulation ergometer (study 5) with the existing ergometers (table 2), the ergometer construction and biofeedback system is very innovative. The correct hydrodynamic concept of this emulation ergometer adds knowledge to the research area of sailing ergometers. Additionally, it is in our opinion of great value for the accuracy of the physiological findings presented in this dissertation.

3. Mechanisms during sailing-specific submaximal quasi-isometric knee extension exercise

It has been established that during upwind sailing, heart rate significantly increases up to 75 % HR_{peak} and oxygen uptake (VO_2) significantly increases up to 40 % VO_2peak. These disproportionate increases reflect the isometric tension put on the anterior body muscles (Vogiatzis et al., 1995). Also, the significant increases in both systolic (due to an increased peripheral resistance) and diastolic blood pressure (in order to increase intrathoracic pressure) indicate the isometric nature of this exercise (Blackburn, 1994). However, lactate concentration ([La]) during upwind sailing does not exceed 4 $mmol \cdot l^{-1}$, suggesting only a small oxygen and energy deficit during upwind sailing exercise (Vogiatzis et al., 2008). As a consequence, researchers reached consensus to use the term *quasi-isometric* to identify hiking exercise (Spurway, 2007). Since the cardiorespiratory, -vascular and metabolic demands during upwind sailing have been thoroughly investigated in the past, this dissertation further emphasises the muscular mechanisms during upwind sailing exercise.

Muscular mechanisms

The electromyography registration during a sailing-specific submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing exercise) demonstrates a significant decrease in mean power frequency (MPF) (study 2, 3 & 5) and increase in root mean square (RMS) (study 3 & 5) indicating an increased state of muscle fatigue and increased recruitment of other motor units (Coburn et al., 2005). Also, deoxygenated hemo- and myoglobin concentration (deoxy[Hb+Mb]) – as an indication of microvascular oxygen extraction (Boone et al., 2010; Celie et al., 2012) – significantly increases during submaximal (quasi)isometric knee extension exercise (study 2, 3 & 5). Reoxygenation – as an indication of oxygenated blood inflow into a tissue that had previously been oxygen deficient due to exercise (Poole et al., 2011) –, however, did not significantly increase or decrease during upwind sailing exercise (study 3 & 5), but showed a significant decrease for Optimist sailors during submaximal isometric knee extension exercise (study 2).

Focusing on one bout of sailing-specific submaximal (quasi-)isometric knee extension exercise (study 2), this bout appears to consist of 3 phases. At exercise onset (0 s to 30 s), the balance between oxygen supply and oxygen demand is clearly disturbed. To minimize the oxygen deficit, deoxy[Hb+Mb] increases sharply as an indication of increase in oxygen extraction. Subsequently (30 s to 90 s), the balance is restored as deoxy[Hb+Mb] stabilizes and reaches a steady state phase. Finally (90 s tot 96 s), as a result of the muscle relaxation (as a representation of tacking) and a decreased intramuscular pressure, it is suggested that there is a sudden outflow of deoxy[Hb+Mb] (i.e., reoxygenation of the tissue under the NIRS-probe). The steady state phase in deoxy[Hb+Mb]pattern suggests that capillary blood flow in the muscle is probably not occluded (study 2). This is in line with the results of Moalla & colleagues (2006) who found in a pediatric population during submaximal knee extension exercise at 50 % maximal voluntary contraction (MVC) that at 50 % of total endurance time a plateau in saturation was reached and lasted until the end of exercise.

Parallel observation of these 4 muscular parameters throughout the entire upwind sailing protocol on a sailing ergometer (study 3 & 5) establishes two or even three different phases (study 3 & 5). First, as a result of exercise onset, mean power frequency (MPF) decreases, root mean square (RMS) increases and deoxy[Hb+Mb] increases, indicating an increase in muscle fatigue, additional motor unit recruitment and microvascular oxygen extraction respectively. In the second phase, a steady state in all parameters is observed (study 3 & 5). It is suggested that after the demanding starting phase, sailors try to stabilize the muscular and metabolic demand by using several compensation strategies (study 3 & 5). It could be suggested that sailors adapt their intramuscular (i.e. between different muscle fibers) or intermuscular (i.e. between different synergistic muscles) coordination pattern to meet the muscular demand (Maïsetti et al., 2006; Boyas et al., 2009). A compensation strategy can be attributed to the active recovery during tacking. During the tack, sailors get up and change boat side. At this point, relaxation and gravity causes a rapid outflow of deoxygenated blood that was trapped in the muscle due to the increased intramuscular pressure and a rapid inflow of oxygenated blood. According to reoxy[Hb+Mb] results, about 20 to 40 % of the deoxy[Hb+Mb] under the probe is in this way substituted by fresh oxygenated [Hb+Mb] (study 2, 3 & 5). As such, sailors probably benefit not only from the abovementioned tacking movement, but also from other fore and aft body movements or the alternate-legs-strategy (Spurway, 2007). This technique consists of a momentary relaxation (and thus recovery) of one of the lower limbs while the other lower limb keeps on hiking alone. Further, the third phase during the protocol demonstrates a second decrease in MPF, increase in RMS and deoxy[Hb+Mb], reflecting the increase in muscular demand and level of muscle fatigue, despite no increase in hiking intensity (study 3). The simultaneous RMS-increase and deoxy[Hb+Mb]-increase can indicate an additional recruitment of muscle fibers, probably fast twitch fibers (Ferreira et al., 2005; Boone et al., 2010). During the final bout, this progress in MPF, RMS and deoxy[Hb+Mb] is even further enhanced by a greater metabolic and muscular demand that is required as a simulation of the struggle on the water to get as first one around the upwind mark. During this last phase, it could be thought that oxygen availability is reduced as a consequence of a restricted blood flow (study 3), however the study of Vogiatzis & colleagues (2011) suggested that blood flow velocity was not limiting during hiking.

Differences between untrained and specifically trained boys (i.e. optimist sailors)

During sailing-specific submaximal (quasi-)isometric knee extension exercise, sailors demonstrate a higher (and continuous) increase in deoxy[Hb+Mb]-increase, compared to the untrained controls (study 2). It suggests that they show a higher (and continuous) increase in microvascular oxygen extraction compared to untrained controls which is in line with the results of Usaj who suggested that a certain number of capillaries open as a result of isometric endurance training, which then increases oxygen consumption as a result of increased oxygen availability (Usaj, 2001).

Research has shown that the neuromuscular activation pattern is changed due to training adaptation (Maïsetti et al., 2006; Boyas et al., 2009). Changes in MPF and RMS have been observed to be largely in parallel to those of deoxy[Hb+Mb] (study 2), suggesting that the higher deoxy[Hb+Mb]-increase in sailors compared to controls is probably related to the different muscle fiber recruitment resulting in less fatigue development. Therefore, it is suggested that sailors acquire slow twitch fibers with a higher oxidative capacity than those of the controls (Pääsuke et al., 1999; Häkkinen et al., 2003), resulting in a higher strength endurance capacity but not in higher maximal strength capacity (Cohen et al., 2010) (study 2). Hence, it is possible that sailors will be able to modify their muscle activation pattern (Mitchell et al., 2011), presumably by recruiting primarily type I fibers (Lucia et al., 2000), indicated by the continuous increase in deoxy[Hb+Mb] throughout protocol, whereas for the same period of time, untrained controls will have to recruit faster their more fatigable type II fibers, indicated by the steady state in deoxy[Hb+Mb] during the second half of the protocol (study 2).

The lower reoxygenation index (RI) for sailors compared to untrained controls is at first sight very surprising. However, it should be argued that reoxygenation index (RI) does not reflect muscle reoxygenation, but reoxygenation of [Hb+Mb] under the NIRS-probe, situated in the microvascular blood vessels. In line with Kime & colleagues (2003), it is hypothesized that sailors exhibit a slower RI which is presumably due to the higher oxidative capacity and thus the higher muscular oxygen extraction from the M. vastus lateralis for sailors compared to untrained controls. As a consequence, the oxygen gradient from capillary blood to myocyte at the onset of blood reperfusion will be higher in sailor compared to controls. Consequently, the sailors will be able to compensate the oxygen imbalance in the M. vastus lateralis itself more rapidly, but this will result in a slower reoxygenation of [Hb+Mb] under the NIRS-probe, because of a very fast muscle oxygen extraction of [Hb+Mb]. Moreover, results confirm that the speed and magnitude of microvascular oxygen extraction during this type of exercise is a very important factor influencing the RI (Kime et al., 2003).

Strategies to extend hiking endurance

Based on the results from study 1, where knee extension endurance capacity is designated as a determinant of sailing performance, several additional strategies can be suggested from scientific point of view to improve sailing-specific submaximal (quasi-) isometric knee extension endurance time (figure 2).

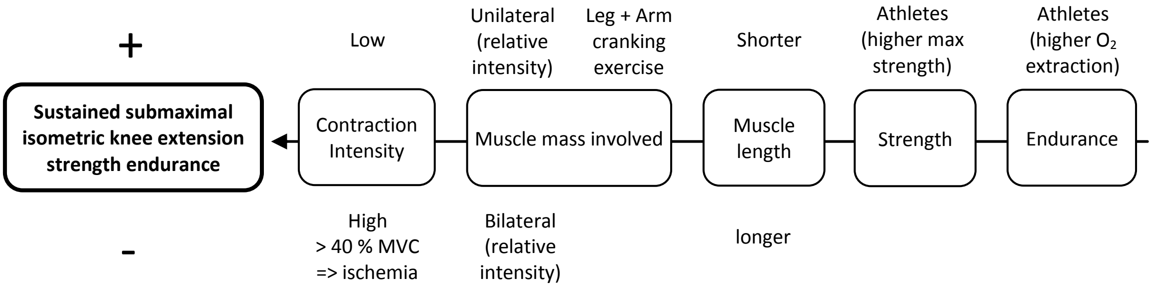


Figure 2: *Overview of the contributing factors to sustained submaximal isometric knee extension strength endurance.*

As indicated in the introduction the contraction intensity significantly influences the endurance time. Therefore, it is suggested that sailors attempt to reduce hiking intensity to the lowest degree possible. However, at the beginning of the regatta, hiking intensity cannot be compromised. Making a good start, taking immediately a good place in terms of wind and current, is very important for the outcome of the regatta. Moments following the start, sailors probably try to reduce and stabilize the metabolic and muscular demand maintaining good boat speed in order to prolong hiking duration. It is thought that during this steady state phase M. vastus lateralis knee extension intensity should be reduced to more or less 30 to 40 % maximal voluntary contraction (MVC), because at this intensity intramuscular pressure is insufficiently high to cause obstruction and thus oxygen deficit (Zwarts & Arendt-Nielsen, 1988). Towards the end of the first upwind leg, sailors probably need to increase metabolic and muscular demand in order to fetch the upwind mark fast without too much energy expenditure.

According to literature, the muscle mass involved should be contributing to submaximal isometric knee extension strength endurance, indicating a longer endurance time in unilateral knee extension exercise at 20 % unilateral MVC, compared to bilateral knee extension exercise at 20 % bilateral MVC (Matkowski et al., 2011). However, the bilateral MVC is not surprisingly higher than the unilateral MVC. This is in contrast to the sailing specific situation where hiking is exerted at an absolute intensity and not relatively to body weight or MVC. As a result, it is thought that hiking on one leg while relaxing the other leg for a few seconds (i.e. alternate-leg-strategy) can be beneficial for hiking endurance, but not when applying this constantly. Another issue related to muscle mass is the influence of intensive arm cranking to knee extension endurance time. As the study of Easton & colleagues (2007) showed a higher endurance time during sustained submaximal isometric knee extension exercise combined with arm cranking exercise (above the lactate threshold). It was suggested that this could be due to an increase lactate concentration ([La]), shuttled from the arms to the M. vastus lateralis, can be taken up there and converted back to pyruvate and taken into the mitochondria as a supplementary metabolite (Easton et al., 2007).

The influence of muscle length has already been investigated extensively and shows a higher endurance time in shorter muscle length (Place et al., 2005; Kooistra et al., 2005; De Ruiter et al., 2005). Transferring these finding to the sailing specific area, it is suggested that hiking with more extended knee (and thus shorter muscle length) is more economic than with more bended knees. Place & colleagues (2005) suggests that this difference is due to a different excitation-contraction coupling whereas Kooistra & colleagues (2005) and De Ruiter & co-workers (2005) suggest that this is due to differences in metabolic cost (i.e. oxygen consumption).

As previously indicated in literature (Pääsuke et al., 1999; Usaj, 2001, 2002; Felici et al., 2001; Halin et al., 2002), endurance time is related to maximal strength, even when the contraction intensity is set at relative intensity (i.e. % MVC). According to the studies of Halin & colleagues (2003) and Felici & colleagues (1999), this could be due to a lower MPF-decrease in athletes with higher maximal strength resulting in a lower spatial and/or temporal recruitment of the more fatigable fast motor units because strength-trained athletes will contain more glycolytic fibers than untrained athletes (Viitasalo & Komi, 1978). Our findings, indicating a relation between MPF-decrease and maximal strength (study 5), are greatly in line with those suggestions.

According to study 5, the rate of fatigue is a predictor of ranking (adj R^2 = 46.5 %; $p = 0.018$) (study 5), suggesting the importance of mechanisms causing or postponing fatigue during sailing performance. As mentioned above, higher maximal strength might improve submaximal isometric knee extension strength endurance which is supported by our findings indicating a relation between MPF-decrease and maximal isometric quadriceps strength (IsomQ) and concentric quadriceps strength (ConcQ) with IsomQ as a predictor of rate of fatigue (reflected by MPF-decrease) (study 5). Transferring this to the field, it is obvious that sailors with a higher maximal strength will show less muscle fatigue, because in real-life the wind force is more or less equal for everyone. Thus, sailors with a higher maximal strength will need to address a lower percentage of their maximal strength compared to sailors with a lower maximal strength. According to literature, also aerobic endurance could extend submaximal isometric knee extension strength endurance. However, the results in study 5 do not support this hypothesis. This could be due to the homogeneous level of aerobic fitness, as reflected by small standard deviation in peak oxygen uptake ($VO_2peak = 57.1 \pm 4.2\ ml \cdot min^{-1} \cdot kg^{-1}$).

To conclude, the research findings demonstrate a significant MPF-decrease, RMS-increase and deoxy[Hb+Mb]-increase at the muscle level during one leg of upwind sailing exercise. Parallel observations of these parameters show 3 distinct phases: (1) a starting phase (where the physiological demand increases), (2) a steady state phase, (3) an ending phase (showing onset of muscle fatigue). Hence, this steady state phase is probably typical for sailors who manage to postpone exhaustion by using different kinds of compensation strategies in order to change inter- or intramuscular muscle fiber recruitment pattern or muscular oxygen extraction pattern. Tacking which is mainly used as sailing technique causes moments of reoxygenation at the muscle level. Reoxy[Hb+Mb]-values during tacking indicate that 20 to 40 % of deoxy[Hb+Mb] under the probe is substituted by fresh oxygenated [Hb+Mb].

A model that clarifies the mechanisms related to the determinants of dinghy sailing performance

A model was developed (figure 3) in an attempt to clarify the physiological mechanisms related to the determinants of dinghy sailing performance explored in this research. The model shows two research levels: findings based on field tests (underneath the horizontal line) and findings based on laboratory tests (above the horizontal line). Lab experiments established the importance of onset of muscle fatigue could be established for both Optimist and Laser sailors. It is assumed that in the Optimist group fatigue is related to different patterns of microvascular oxygen extraction (i.e. presumably related to different oxidative capacity due to training) whereas in the Laser group fatigue is related to maximal isometric quadriceps strength. Optimist sailors' strength is probably also related to sailing performance. However, the results did not indicate this, probably because characteristics such as motor coordination skills, which are more crucial to develop in this age group. Moreover, the model also indicates the role of maximal aerobic endurance as a requirement for the high training load and fast recovery needed during high level regatta's. Important is also the crucial role of sailing practice (i.e. technique training etc.) reflected in this model. However, it should be argued whether this finding is a cause or consequence of sailing level.

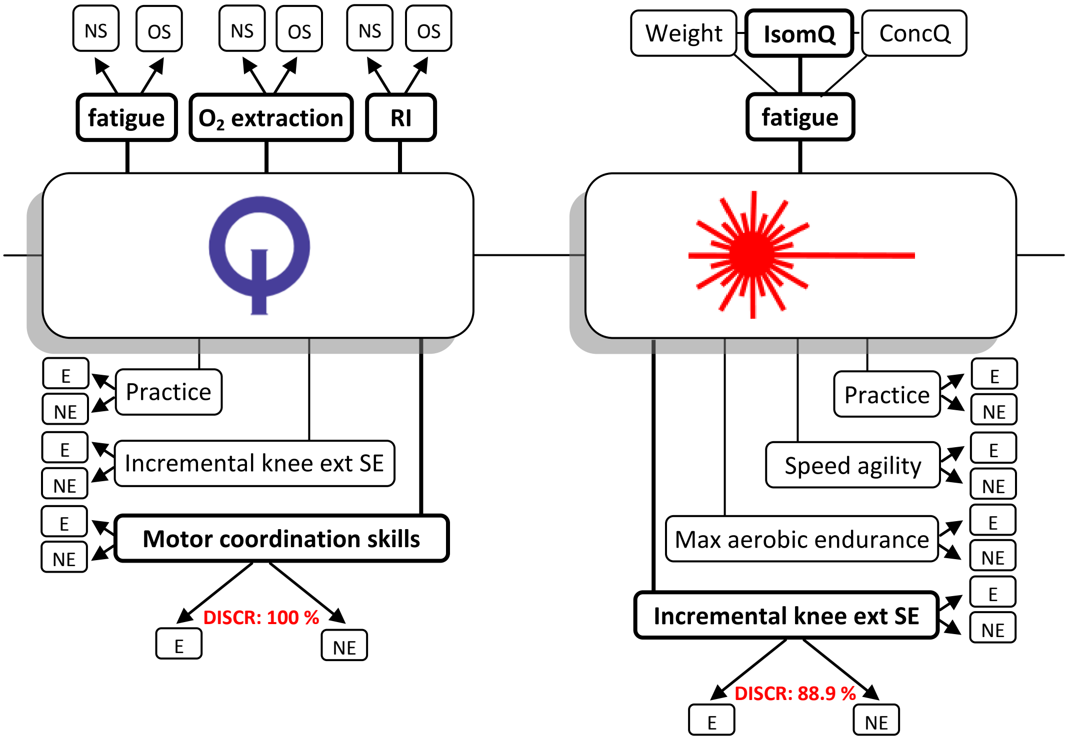


Figure 3: *Overview of significant differences, discriminating factors (DISCR) and related factors to dinghy sailing performance in Optimist and Laser sailors. (Ϙ = Optimist sailors, ✱- = Laser sailors, NS = non sailors, OS = Optimist sailors, E = elite, NE = non-elite, SE = strength endurance, IsomQ = maximal isometric quadriceps strength, ConcQ = maximal concentric quadriceps strength, RI = reoxygenation index)*

To conclude, this research indicates the importance of motor coordination skill training in Optimist sailors and maximal strength training in Laser sailors in order to compensate onset of muscle fatigue during hiking exercise which contributes to a better sailing performance.

4. Strengths and limitations:

This research is that it provides an integrated view on the mechanisms related to the determinants of (upwind) sailing performance (table 3) which is its main strength. Furthermore, this research closes several gaps in sailing literature, including the gap on the physiology and determinants of Optimist sailing performance. This research hereby adds proficiency to the evaluation of different youth sailors, each in their phase of development. This dissertation also provides a scientific basis to optimize the development of a young athlete’s physical capacity up to elite adult sailor.

Table 3: *Overview of the studies on the determinants of sailing performance, the cardiorespiratory, cardiovascular & metabolic responses during hiking, the muscular responses during hiking and the sailing ergometers in literature.*

	Optimist sailors		Laser sailors	
	Studies	Measurements	Studies	Measurements
Determinants of sailing performance	Study 1	motor coordination skills	Blackburn & Hubinger, 1995	Bucket test, sheeting power, handgrip S, max KE S, aerobic fitness, weight
	Study 2	fatigue, fiber recruitment pattern, oxygen extraction pattern	Tan et al., 2006	hiking moment over 180 s, weight
			Vangelakoudi et al., 2007	45 % MVC KE SE test on hiking ergometer
			Aagaard et al., 1998	maximal knee & trunk extensor S
			Study 1	Bucket test (isometric KE SE)
			Study 5	fatigue, max isometric quadriceps S
Cardiorespiratory, cardiovascular & metabolic responses during hiking	***On-water study:*** Rodio et al., 1999		***On-water studies:*** Gallozzi et al., 1993 Vogiatzis et al., 1995 De Vito et al., 1996 Cunningham, 1996 Castagna et al., 2004 Castagna & Brisswalter, 2007	
	Simulation study: Rodio et al., 1999 Study 2		***Simulation studies:*** Vogiatzis et al., 1993, 1996 Blackburn, 1994 Cunningham et al., 1998 Felici et al., 1999 Cunningham & Hale, 2007 Vangelakoudi et al., 2007 Study 5	
Muscular responses during hiking			Maïsetti et al., 2006; Boyas et al., 2009	Electromyography
	Study 2	EMG & NIRS	Vogiatzis et al., 2008, 2011	Near infrared spectroscopy
			Study 5	EMG & NIRS
Hiking ergometers	Rodio et al., 1999		Blackburn, 1994	static ergometer, measuring RM and HSL
	Study 2	static ergometer, measuring HSL	Felici et al., 1999	static ergometer, measuring RM
			Vogiatzis et al., 1996, 2008, 2011	static ergometer, measuring HSL
			Cunningham & Hale, 2007	quasi-static ergometer, measuring RM
			Maïsetti et al., 2006; Boyas et al., 2009	static ergometer, measuring RM
			Study 4 & 5	emulation ergometer: static ergometer, measuring RM

Note: HSL = hiking strap load, RM = uprighting moment, KE = knee extension, SE = strength endurance, S = strength.

The upwind sailing emulator was biologically validated by calculation of the Error Score (ES). However, it should be emphasized that only the validity and not the reproducibility of this emulator was shown. Nevertheless, it should be noted that ES is a biological value that represents the difference between a mathematical developed signal and a man-produced signal. Therefore, it could be expected that the difference between both would be notable. The fact that ES turned out to be only 4.1 ± 1.8 % indicated that the developed protocol was highly useful to work with. In addition, also the sailors themselves clearly indicated that this test protocol is a good representation of upwind sailing on the water.

One could emphasize that there are still several differences between emulated and on-water upwind sailing. The first difference between real-life sailing and this emulation is probably the randomness of the weather and water conditions which are not present in the laboratory. However, it was the intention to exclude these from the experiments in order to create a standardized protocol. Secondly, during real-life sailing, each tactical or technical decision or movement you make will have its consequence on the further time course of the race. This will not be the fact during this emulation where the protocol cannot be manipulated by the sailors' movements (in contrast to a simulation). This also eliminates the influence of sailing technique and tactic and thus the possibility to evaluate sailing technique or tactic during this test. A third difference is the fact that the required HM during this emulation is relative to the sailors maximal HM, whereas in real-life the wind and weather conditions are the same for every sailor, obviously dependent on their boat (and body) location or position in the race. Fourthly, the boat is positioned horizontally and does not move during protocol. This is totally different than during on-water sailing and could induce different joint angles during sailing exercise on the emulator compared to on-water. However, a good sailor keeps his boat as flat as possible on the water (by minimizing boat roll and pitch) in order to minimize speed loss. To elaborate on the ingenious-technical issue, the elimination of this limitation can only be realized by modifying the static connection between the base frame and the boat by a set of actuators that are actively controlled in interaction with the forces exerted by the subject. This is done by converting the present measuring from an emulator to a genuine sailing simulator. Further, although the correct loads are put on the rudder and mainsheet, the loads are not imposed and thus not controlled. Since it is suggested that an accurate performance of this exercise does not have a highly considerable influence on the physiological responses, we think this is not the biggest limitation of this ergometer. In addition, to date, the upwind sailing ergometer can only emulate the upwind leg. However, for future research it would be interesting to create an emulation of a full race, by implementing another load cell which measures (besides roll) also pitch moment. In this way, physiological responses to a full regatta could be investigated. In addition, it should also be noted that this study only demonstrated the validity and not the reproducibility of this upwind sailing ergometer.

In terms of future research, there is definitely space for improvement in the validation of this or another ergometer. For future protocol development, we would suggest to base the protocol on a real-time registered signal during a preliminary sailing experiment. In that way, the required HM will vary more natural and inartificial.

5. Practical applications and development of sailing athletes:

In terms of practical implementation, this emulation ergometer is very useful for exercise testing in a sailing specific situation (i.e. Quasi-isometric exercise addressing specific muscles), because the same sailing protocol can be imposed on different sailors or on the same sailor on different occasions. Therefore, this is the optimal tool for sport specific performance diagnostics and follow-up of the training process. In addition, the technical advantage of this ergometer is also that the base frame can be used for any type of dinghy. Thus, not only Laser sailors can be tested on this ergometer, but also other dinghy sailors (e.g. Optimist sailors, Finn sailors, etc.). As such, this ergometer can easily be used as sport specific training and evaluation tool (i.e. to measure physical adaptation in sailing before and after training periods).

Concerning training, the findings of this research demonstrate the fundamental importance of implementing motor coordination skill training for Optimist sailors. This reflects the importance of a good general development of the physical characteristics for children in order to build a good physical framework. The Long Term Athlete Development (LTAD) theory suggests that the ‘window of accelerated adaptation to motor coordination’ is between 9 and 12 in boys and between 8 and 11 in girls (Balyi & Way, 2005). Therefore, it is assumed that coaches should focus on developing fundamental movement skills (not only in sailing but in general) during this age stage. If fundamental motor skills are not developed in this stage, a significant window of opportunity has been lost, compromising the ability of the young athlete to reach his/her full potential (Balyi, 2004; Balyi & Way, 2005). Later on, dinghy sailing performance turns out to be strongly determined by muscular strength demonstrating the implementation of a well-balanced strength training program. However, this should be linked to endurance training in order to enhance maximal and submaximal aerobic endurance. This could be a prerequisite to manage the high training load and have a fast recovery, which is needed during high level regatta’s.

For the development of sailing athletes, we should consider 3 different phases: talent detection (TDET) (i.e. the discovery of potential performers who are currently not involved in the sport (Mohamed et al., 2009)), identification (TID) (i.e. the process of recognizing current participants with the potential to excel in a particular sport (Vaeyens et al., 2008)) and development (TDEV) (i.e. providing the most appropriate learning environment to realize this potential (Vaeyens et al., 2008)).

In order to develop a test battery for talent detection, identification or development with severe limits in time and materials, the following tests should be retained. It is crucial to include the anthropometrical measurements (body height, sitting height, body weight, skinfolds) and the KTK-test battery, to detect talent and to look for general sports potential. The anthropometric measurements are not time consuming, they estimate the maturation status and adult body height of the child (Mirwald et al., 2002; Sherar et al., 2005). The latter estimations are of great value for coaches of young to adolescent sailor; on the one hand in order to interpret the physical characteristics and technical/tactical sailing performance of young athletes, and on the other hand in order to decide when to change the Optimist for another dinghy (i.e. often already before 15 years) and more importantly 'to what dinghy?'. The latter decision is partially based on (future) body dimensions (see table 10 in the introduction for optimal body dimension). Besides that, this decision is also dependent on their physiological, technical and tactical capacities. Moreover, when moving on from Optimist sailing to the next level, it is important to further develop and improve the physiological, technical and tactical capacities by sailing temporary a boat type that helps the sailor to improve their weaker or unexplored capacities. The KTK-test battery is in our opinion crucial for the detection of young athletes with potential to excel in sports. Moreover, the Long Term Athlete Development (LTAD) indicated that 'the window of accelerated adaptation to motor coordination' is between 9 and 12 years for boys and between 8 and 11 years for girls (Balyi & Way, 2005). If fundamental motor skills are not developed in this stage, a significant window of opportunity probably has been lost, compromising the ability of the young athlete to reach his/her full potential (Balyi, 2004; Balyi & Way, 2005).

Research suggests that the bucket test can further help to differentiate between elite and non-elite Optimist sailors, who are the big pool for talent identification. The bucket test is particularly useful given the higher emphasis on and influence of strength endurance capacity on sailing performance.

For talent identification and evaluation within the dynamic adolescent sailors group (i.e. Laser, Europe, Laser 4.7, Laser Radial, etc.), it is advised to use the anthropometrical measurements, the bucket test, the handgrip test and the 20m SR to have an idea for the maximal endurance capacity. According to several studies (Blackburn & Hubinger, 1995; Aagaard et al., 1998; Tan et al., 2006; Vangelakoudi et al., 2007), strength endurance is an important indicator of sailing performance and even a significant test discriminating for 100 % of the elite from the non-elite dynamic sailors. Therefore, the bucket test is a not-to-be missing sport specific test. Maximal strength can also be considered as an important indicator of sailing performance in dynamic sailors (Aagaard et al., 1998; Tan et al., 2006). An easy (requires no expensive equipment) and no time consuming test to measure maximal static whole body strength is the handgrip test (EUROFIT).

For talent development (in the Olympic-ambition team), one can assume to have a higher budget and more time to test the physical capacity in very accurate way. Therefore, two laboratory tests should be conducted: an incremental cycling test (step protocol) and an isometric (if possible also concentric and eccentric) Quadriceps strength test. An incremental cycling test is a very relevant and accurate way to measure maximal aerobic endurance and to get insight into the submaximal thresholds (because it is a dynamic and weight-supported exercise which addressing mainly the Quadriceps muscle). Also a rowing exercise test could be considered (because it addressed more or less the same muscle in a comparable anatomical and biomechanical condition as during sailing exercise (Malte, 2000). However, a basic knowledge of the rowing technique is required to use it to determine the maximal aerobic endurance (Fletcher, 2008). Further, an isokinetic strength test is also a very relevant and accurate way to test maximal isometric, concentric and/or eccentric strength. Isometric Quadriceps strength is the most important parameter to measure. However, in terms of injury prevention, I could also advise to test the maximal concentric quadriceps and eccentric hamstring strength in order to know the (functional) hamstring-quadriceps ratio to determine the knee stabilization ratio (Bojsen-MØller et al., 2007). A reduced function hamstring-quadriceps ratio indicates an excessive quadriceps muscle contraction that can create significant anterior tibial translation an anterior cruciate ligament (ACL) shear (Bojsen-MØller et al., 2007). Only enough co-activation of the hamstring and quadriceps muscles can provide enough stability to guarantee knee stability.

In terms of performance diagnostics during talent development, it is suggested to conduct 1 laboratory test each year (off-season) in order to determine accurately the physical characteristics and field tests for at least two-monthly follow-up.

In an attempt to clarify my opinion and view on the talent detection (TDET), identification (TID) and development (TDEV) process in one-person-dinghy sailing, a model for development of Flemish Optimist-Laser athletes, based on that of Hohmann & Seidel (2003), was developed (figure 4).

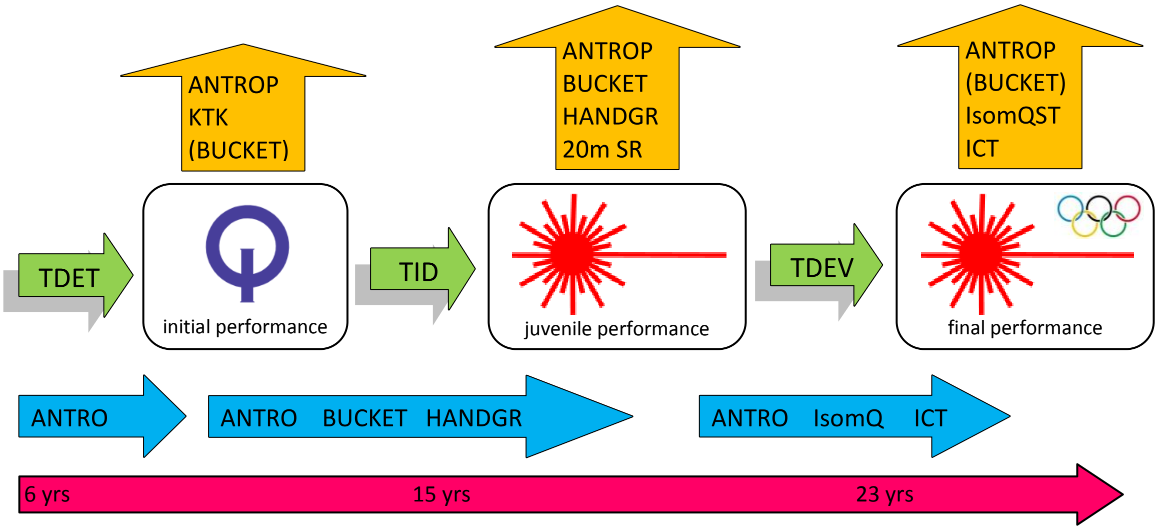


Figure 4: *Model for development of Flemish Optimist-Laser athletes, based on the model of Hohmann & Seidel (2003*). (TDET = talent detection, TID = talent identification, TDEV = talent development, Ϙ = *Optimist sailors,* ✱- = *Laser sailors*)

In order to make a connection with the current policy of the Flemish Yachting Association (Vlaamse Yachting Federatie, VYF) where the Optimist and Laser class gets priority but exists besides other sailing classes and career possibilities, talent detection, identification and development tests were also applied on the current VYF-policy (VYF, 2014) (figure 5).

In the talent detection phase (‘niveau 4’ in figure 5), the challenge is on the on hand to get children out on the water to initiate them in the sport (and orientate them to a club) and on the other hand to detect the children with potential for performance in sports in general. It is at that moment that they are stimulated to try and carry on sailing. The Flemish Yachting Association guarantees this inflow by means of the ‘IkZeil/IkSurf’ project, ‘de watersportdag’, the Q-cup (i.e. a competition for kids ≤ 13 years with ± one week of sailing experience up to the day where you have been competing at 2 national regatta’s) and the VYF-Optimist-introduction weekend (VYF, 2014). In the talent identification phase the focus is on the Laser-development-line (i.e. development from Optimist through Laser 4.7 (or Europe, Splash) to Laser radial (for women) or standard (for men)). However, career switches to the two-man-dinghies are always possible. In this phase the Flemish Yachting Association puts a lot of effort in the different Optimist groups and talent teams (‘niveau 3’ in figure 2). Every team has their specific coaches and, training and competition program. All these ‘teams’ are under the supervision of the ‘topsport’ commission. In the talent development phase, ‘niveau 2’-athletes are practicing together with ‘niveau 1’-athletes in order to create a challenging sailing environment to keep pushing the performance limit. According to a holistic ecological perspective on talent development in elite sailors which highlighted the central role of the athletes overall environment, this can be assumed as a very good way to create environments that nurture sailing talent (Henriksen et al., 2010). This team is also situated with the ‘BE GOLD’-project where athletes of different sports are aiming for Olympic success (Vlaamse Gemeenschap, 2014).

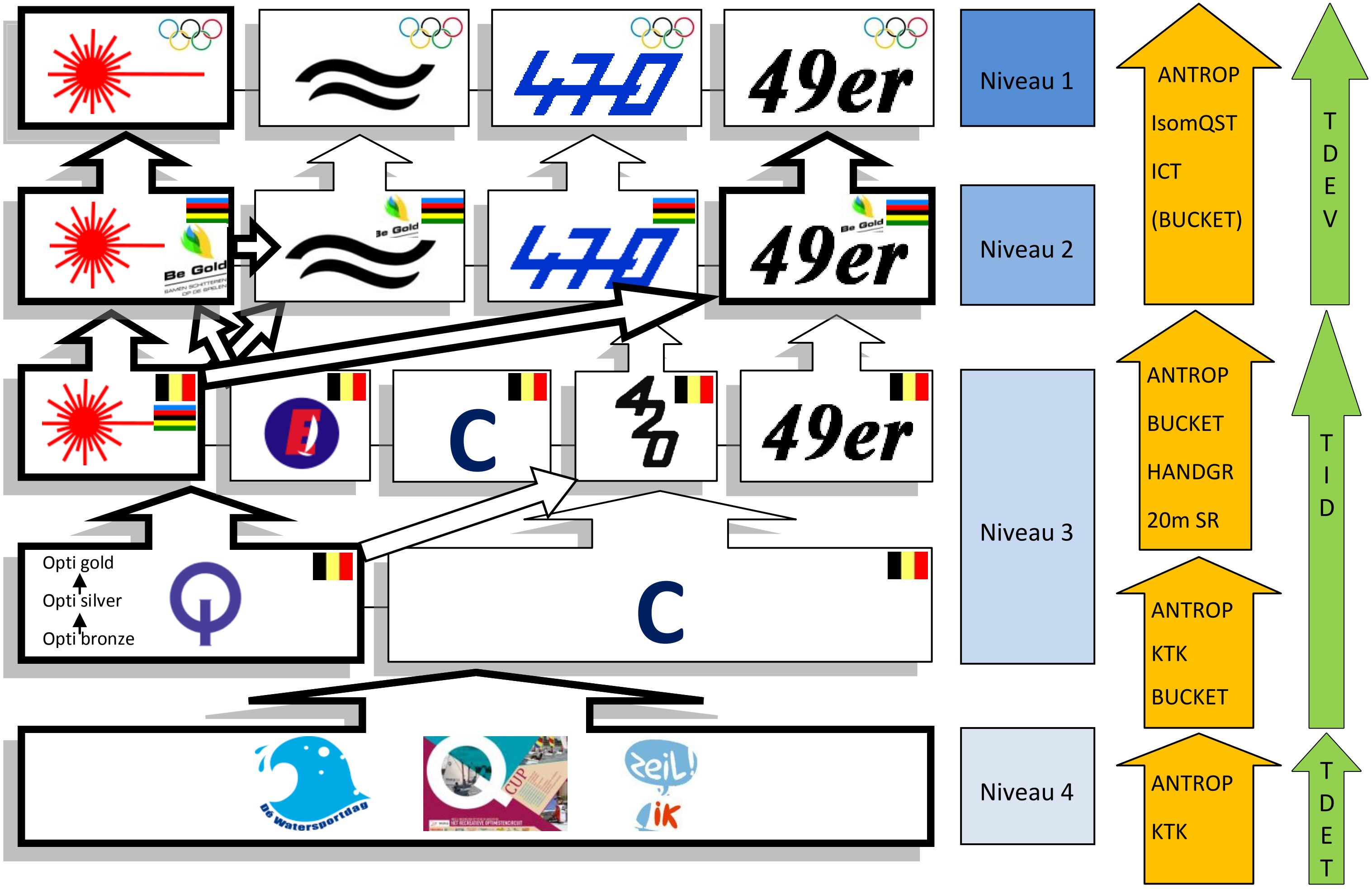


Figure 2: *Talent detection, identification and development model of the Flemish Yachting Association (VYF). (the flags in the upper right corner indicate the national, international or Olympic competing level) (Ϙ = Optimist dinghy, ⁎- = Laser dinghy, E = Europe dinghy, c = cadet dinghy, ≈ = Finn dinghy)*

6. General conclusions:

The present dissertation enhances our understanding of dinghy sailing performance by focusing on three research aims:

AIM 1: Determinants of dinghy sailing performance

Dinghy sailing performance for Optimist sailors is highly related to motor coordination skills, whereas for dynamic adolescent hikers it is related to incremental (quasi-)isometric knee extension strength endurance (i.e. performance on bucket test). The contribution of incremental (quasi-)isometric knee extension strength endurance to performance is for both Optimist and Laser sailors related to the delay of fatigue onset which is clearly related to maximal quadriceps strength for Laser sailors.

AIM 2 : Innovation in sailing ergometers

A biologically validated upwind sailing emulation ergometer was developed, by applying a biofeedback system to the measurement of hiking moment. Thereby, a certain quasi-isometric upwind sailing protocol could be imposed which allows the researcher to define the exact sailing conditions for several subjects or to one subject on different occasions. This emulation ergometer can be used as tool for sport specific performance diagnostics and follow-up of the training process (i.e. to measure physical adaptation in sailing before and after training periods).

AIM 3 : Mechanisms of submaximal (quasi-)isometric knee extension exercise

During a submaximal (quasi-)isometric knee extension exercise (as a part of upwind sailing exercise), fatigue (as reflected by an MPF-decrease and RMS-increase) developed. However, after an initial increase, a steady state phase was observed. It is assumed that this steady state phase in the middle of the upwind leg is due to compensation strategies (i.e. tacking, fore and aft movements, alternate-legs-strategy) conducted by the sailors in order to delay exhaustion.

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A1:

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Science happening VLIZ (June 6, 2014: Ostend, Belgium): “World Oceans Day”

Bourgois J, **Callewaert M**, Celie B (2014). “Did you ever fall into cold water? Get out before you die…” Physiology of cold water immersion (poster presentation).

V:

Organization symposia: Research Project “Olympic Dinghy Sailing 2009-2012”

Physical fitness training for sailors (October 10, 2009: Ghent)

Presentation research project (November 26, 2009: Ghent)

Screening tests for sailors: presentation protocol & main results (coaches) (November 30, 2009: Ghent)

Screening tests for sailors: presentation protocol & main results (athletes & parents) (December 4, 2009: Ghent)

Fitness training for sailors on a rowing ergometer (March 2, 2010: Ghent)

Mental coaching “momentum” (June 20, 2010: Ghent)

Nutrition and hydration in sailing (November 23, 2010: Ghent)

Screening & field tests for sailors: protocol & main results (coaches) (February 1, 2011: Ghent)

Screening & field tests for sailors: protocol & main results (athletes & parents) (February 3, 2011: Ghent)

Mental Coaching for sailors (May 14, 2011: Newport)

Physical training guidelines for sailors (May 15, 2011: Newport)

Regulation and meteorology in sailing (October 15, 2011: Newport)

Screening & field tests for sailors: main results (coaches, athletes & parents) (March 1, 2012: Ghent)

Nutrition for sailors (May 12, 2012: Newport)