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Title: Physical requirements in Olympic sailing

J. BOJSEN-MØLLER[1], B. LARSSON[2], P AAGAARD[3]

[1]*Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway,*
[2]*Team Danmark, The Danish Elite Sports Association, Copenhagen, Denmark*
[3]*Institute for Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark*

Corresponding Author
Jens Bojsen-Møller, Professor (PhD)
Norwegian School of Sport Sciences
Oslo, Norway
+45 2685 4059
jens.bojsen.moller@nih.no
Additional author Information:

Benny Larsson, Sportsphysiologist
Team Danmark
Idrættens Hus
Brøndby Stadion 20
2605 Brøndby
+45 4326 2521
bela@teamdanmark.dk

Per Aagaard, Professor (PhD)
Head of Muscle Physiology and Biomechanics Research Unit
Department of Sports Science and Clinical Biomechanics
University of Southern Denmark
Campusvej 55, DK-5230 Odense M, Denmark
Ph: +45 2347 4826
paagaard@health.sdu.dk

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Abstract
Physical fitness and muscular strength are important performance parameters in Olympic sailing although their relative importance changes between classes. The Olympic format consists of 8 yacht types combined into 10 so-called events with in total 15 sailors (male and female) in a complete national Olympic delegation. The yachts have different requirements with respect to handling and moreover, each sailor plays a specific role when sailing. Therefore physical demands remain heterogeneous for Olympic sailors. Previous studies have mainly examined sailors where "hiking" (the task of leaning over the side of the yacht to increase righting moment) is the primary requirement. Other than the ability to sustain prolonged quasi-isometric contractions, hiking seems to require significant maximal muscle strength in especially knee extensors, hip flexors and abdominal and lower back muscles. Another group of studies have investigated boardsailing and provide evidence to show that windsurfing requires very high aerobic and anaerobic capacity. Although data exists on other types of sailors, the information is limited, and moreover the profile of the Olympic events has changed markedly over the last few years to represent more agile, fast and spectacular yachts. The change of events in Olympic sailing has likely added to physical requirements however, data on sailors in the modern type yachts are scarce. The present paper describes the recent developments in Olympic sailing with respect to yacht types, and reviews the existing knowledge on physical requirements in modern Olympic sailing. Finally recommendations for future research in sailing are given.

Keywords: yachting, hiking, endurance, strength, physical requirements

1. Introduction

Olympic sailing is a complex sport that comprises numerous performance parameters such as the ability to understand and foresee weather conditions, optimal equipment such as yacht and sails, and technical and tactical understanding (Bojsen-Møller, Larsson, Magnusson & Aagaard, 2007; Spurway, Legg & Hale, 2007). In addition, physical fitness of the sailor(s) contributes to overall performance, and the importance of e.g. muscle strength, muscle endurance and aerobic and anaerobic capacity has continuously increased in recent years. The physical requirements have changed due to a more fierce level of international competition, but also in consequence of changes in the Olympic sailing format.

Our knowledge about the specific physical requirements for Olympic sailing has improved over the recent years (Aagaard et al. 1998; Larsson, Beyer, Bloend, Aagaard & Kjaer 1996; Marchetti, Figura & Ricci, 1980; Niinimaa, Wright, Shephard & Clarke, 1977; Shephard, 1990; 1997), but not all aspects of sail racing have been thoroughly examined. Most studies have evaluated so-called hiking performance where sailors extend their body outside the boat to increase the righting moment (Blackburn, 1994; Cunningham & Hale, 2007; DeVito, Di Filippo, Felici & Marchetti, 1993; Larsson et al. 1996; Mackie, Sanders & Legg, 1999; Putnam, 1979). Although hiking ability is important in some yacht types it is far from all sailors that hike. In fact, the current Olympic format consists of 8 yacht classes, comprising a total of 15 sailor positions/functions of which only 5 involve hiking. Since each of these 15 positions has specific roles with distinct physical demands during racing, it follows that the existing knowledge on the position specific physical requirements in Olympic sailing remains limited.

Studies on the physiology of sailing are in general limited by the difficulty to perform valid and consistent on-water data recording. Measurements of physiological responses to actual sail racing have not been reported, however, proxy data exist that are based on race simulations conducted either on-water or by using laboratory based sailing dynamometers (Blackburn, 1994; Cunningham & Hale, 2007; De Vito, Di Filippo & Felici, 1996; De Vito, Di Filippo, Rodio, Felici. & Madaffari, 1997, Larsson et al. 1996; Mackie et al. 1999; Vogiatzis, De Vito, Rodio, Madaffari & Marchetti, 2002). While measurements obtained during sailing remains the most optimal strategy to infer about physical requirements for competitive sailing, an alternative experimental approach is to examine a number of elite athletes with respect to more standardized measurements. A combination of these methods will likely provide the most feasible approach to gather valid and relevant information.

Therefore, it was the purpose of the present paper to review the available scientific data on physical characteristics of male and female Olympic sailing athletes engaged in the modern competition format. The review is based on existing publications, but also includes a unique dataset that has been made available to the authors through the Danish Elite Sports Association (Team Danmark), where international elite sailors routinely have been tested under highly controlled conditions more than three decades.

2. Olympic sailing

Current Olympic sailing consists of 10 separate events (8 yacht-classes), which all are handled in a different manner, involving either a single or double-handed crew. Furthermore, all events require specific anthropometrics including distinct body weight characteristics, gender, muscular strength and endurance, aerobic/anaerobic capacity and agility skills. Even within a single class sailors may experience different demands depending on their specific position. Consequently, the assessment of physical requirements in Olympic sailing turns out to be a highly intricate task. To reduce complexity, attempts have previously been made to classify Olympic sailors (Bojsen-Møller & Bojsen-Møller, 1999), and along these principles, sailors in the present paper are divided into four groups based on their specific role during sail racing:

1. Hikers, who sit on the deck and lean over the side with their feet fixed under so called hiking straps (Laser, Laser Radial, Finn, 470 helmsman).
2. Side hikers, who by support of hiking straps and a special harness sit prone on the free board outside the boat (Star crew). It should be noted that there will be no side hikers in the coming Olympic games, but data on this group of sailors are nonetheless presented below.
3. Trapezing sailors, who stand on the gunwale or side wings of the boat supported by a wire that is extended from the rigging (49'er, 49'erFX, Nacra 17, 470 crew).
4. Board sailors, who sail on a full planing board where the rig and sail is fixed by a compliant link to the board, and as such free to move by the sailor (RS:X).

The profile of the Olympic events has changed markedly over the last decades to represent more agile, fast, spectacular yachts, which reflects the evolution of yacht design and sailing in general. Consequently also the physiological profile, and type of sailors participating in Olympic sailing has changed: The number of sailors in a full national Olympic team has increased from 11 in 1969, topping at 18 in the 2000- 2008 games, while in 2012 it was reduced to 16, and in 2016 the number will be 15. The number of hikers has decreased from approximately 65% in 1968 to 33% for the coming Olympic games. The percentage of side hikers has similarly decreased and will be zero in the 2016 games. Concurrently the number of trapeze sailors has increased to now represent 53% of all sailors in a full national Olympic delegation. (Fig. 1)

Insert Fig. 1 appr here.

Not only the event format, but also the Olympic racing format has been amended through recent years such that regattas now entail more races that are of briefer duration but with higher frequency. Moreover, shorter racecourses with more mark roundings, rapid maneuvers, and higher intensity have been implemented in many classes, and the most radical format has been tested in the 49'er class where so-called "theatre style racing" comprises very brief races (5-10 min), many laps and maneuvers, short breaks in between races, and up to 8 races per day.

In consequence of such changes in the rules and format of Olympic sailing, the physical demands imposed on sailing athletes will be highly different in the 2016 Olympic games in Rio compared to those of previous Olympic games.

3. Olympic sailing and physical requirements

3.1. Muscle strength

Only very few studies have reported strength data obtained from Olympic sailors. Early papers typically examined muscle strength in isometric handgrip, and during static testing of the elbow flexors/extensors, and knee extensors anticipating that these muscle groups were particularly important for elite sailors. In these studies sailors appeared to be markedly stronger in knee extension and handgrip strength compared to other elite athletes such as rowers, while elbow flexor/extensor strength levels seemed similar to observations in elite swimmers (Ninimaa et al. 1977; Plyley, Davis & Shephard, 1985; Shephard, 1990). More recently, Aagaard et al. (1998) reported isokinetic strength profiles of elite sailors, and found very high eccentric knee extensor muscle strength and trunk extensor strength in Olympic sailors comparable to that of highly strength trained elite athletes in explosive-type sports. A later study (Bojsen-Møller et al. 2007) supported these findings on extreme maximal knee extensor strength in hikers (Fig 2) and extended these findings by also reporting dynamic hamstring/quadriceps (H/Q) strength ratios. Strong hikers displayed relatively low H/Q ratio, which was suggested to induce potential risk of knee joint overload or injury due to an impaired capacity for dynamic joint stabilization (Bojsen-Møller et al. 2007; Aagaard, et al. 1997).

Insert Fig 2 appr here.

With respect to hiking performance, moderate to strong positive correlations have been observed between knee extensor strength and hiking performance (Blackburn, 1994; Aagaard et al 1998; Tan et al. 2006), while positive correlations between hiking performance and trunk flexor and especially trunk extensor strength also have been reported (Aagaard et al. 1998).

"Strength endurance" or "muscular endurance" may be assessed in highly different ways, and typically repeated bouts of isometric or dynamic muscle actions or sustained submaximal isometric contractions have been applied. Olympic sailors (hikers) demonstrated high muscular endurance compared to other athletes as well as trained control subjects (Niinimaa et al. 1977; Plyley et al. 1985). When specific hiking endurance was assessed using a custom built hiking ergometer hikers were able to sustain the required hiking position for +100% longer time compared to a control group consisting of highly trained individuals (non-sailors) (Larsson et al. 1996). Similar findings were reported by Vangelakoudi et al. (2007) where elite sailors showed 50-100% longer time to failure in static and dynamic endurance contraction tasks compared to club level sailors.

3.2. Aerobic and anaerobic capacity

Aerobic capacity of Olympic sailors has been reported with differing results both within and between yacht classes: Larsson et al. (1996) observed rather high VO_2max values in a group of Olympic sailors preparing for the 1992 Olympic games in Barcelona, especially in those athletes who were required to hike when sailing (64 $mlO_2*kg^{-1}*min^{-1}$ for male hikers, 59 $mlO_2*kg^{-1}*min^{-1}$ for male non-hikers, and 50 $mlO_2*kg^{-1}*min^{-1}$ in female hikers). VO_2max values of 62 $mlO_2*kg^{-1}*min^{-1}$ were similarly reported in national elite level Laser dinghy sailors (Blackburn, 1994) along with values of 55 $mlO_2*kg^{-1}*min^{-1}$ in high-level Laser sailors (Cunningham & Hale, 2007). Board sailors appeared to have the largest aerobic capacity with VO_2max values up to 65 $mlO_2*kg^{-1}*min^{-1}$(De Vito et al. 1997; Vogiatzis et al. 2002; Castagna et al. 2007; 2008), whereas trapezing crew in the very dynamic type dinghies have demonstrated values between 57 and 64 $mlO_2*kg^{-1}*min^{-1}$ (Bojsen-Møller et al. 2007). In the opposite range an average VO_2max of 43 $mlO_2*kg^{-1}*min^{-1}$ was recorded in elite sailors which was significantly lower than values obtained in athletes recruited from 10 other sports disciplines (Tsopanakis, Kotsarellis & Tsopanakis, 1986). These early data underscore that physical preparations have not always been an integrated element in elite sailing, and that at least a few decades ago it was in fact possible to perform at high level in sailing despite a limited aerobic capacity.

The Danish Elite Sports Association (Team Danmark) has tested and monitored elite sailors since 1988 and these unique data were made available for the present review. The data are based on more than 400 single physical tests on ~120 sailing athletes examined during a 25-year time period. Parts of these data have been published previously (Larsson et al. 1996; Bojsen-Møller et al. 2007) but a complete overview has not been performed previously. The data corroborate those of previous investigations since side-hikers have aerobic capacities around 50 ml*kg^{-1}*min^{-1}, while trapeze sailors and hikers show somewhat higher capacities (55 ml*kg^{-1}*min^{-1}), and board sailors display even greater values (60 ml*kg^{-1}*min^{-1}) (Fig. 3 A). Within these data, an attempt was made to compare sailors in more classic yachts, to those of modern dynamic 'skiff' type yachts was made, but contrary to what might be expected no difference in aerobic capacity seemed apparent (Fig 3 B).

Insert Fig. 3 appr here.

Anaerobic capacity. Not many studies have examined anaerobic capacity in elite sailors, but Vangelakoudi et al. (2007) reported Wingate test data (30-s all out bicycling) suggesting that sailors have a well-developed capacity to develop high anaerobic power (mean and peak power of ~8 and ~11 W*kg-1 respectively) comparable to that of swimmers and middle distance runners. Notably, the Wingate test outcome (maximal and mean power) was positively correlated with the performance ranking of the sailors examined. Larsson et al. (1996) reported that sailors are superior to otherwise well trained control subjects in a 1-min all-out rope pulling task for the upper extremity (mimicking sail-pumping, which is a repetitive pulling task performed to increase propulsion forces in the sail). Moreover, recent data suggest that anaerobic capacity is highly relevant also in modern type sailing, where especially elite 49'er crewmen reached peak power outputs of 580 W (8 W*kg^{-1}) during maximal upper body pulling tasks (resembling spinnaker hoists), along with 10-s mean values of ~500 W (7 W*kg^{-1}) (Bay & Larsson 2013).

3.3. On-water assessments

No physiological data are available from actual sail racing, but some studies have carried out physiological testing during simulated on-water racing, or by using custom-built sailing simulators situated in the laboratory. With respect to force measurements, Mackie et al. (1999) reported high average hiking strap forces during actual upwind Laser dinghy sailing corresponding to ~80% MVC, along with mainsheet forces (upper extremity pulling) of about 30% MVC. The force loads increased with increasing wind velocity, and were accompanied by large force fluctuations in consequence of the yachts movement in the waves and the sailors response to these movements. Seemingly low muscle activation was observed by Vangelakoudi et al. (2007) where rectus femoris EMG activity during hiking in a laser simulator amounted to ~45% of maxEMG (recorded in a static MVC contraction). In the same study, heart rates of 149 beats*min^{-1} and a corresponding mean blood pressure of 129 mmHg were observed during a 20-min hiking simulations performed with 3 min hiking intervals separated by brief 5-s resting periods. Blackburn (1994) carried out hiking simulations where comparable mean blood pressures were measured (mean BP: 123 mmHg with systolic and diastolic BP of 172 and 110 mmHg respectively). Concurrent heart rates were 60% of max HR while VO_2 during hiking (upwind sailing) corresponded to ~25% of VO_2max, while serum lactate were below 3 mM after repeated hiking bouts. The high blood pressure combined with the somewhat lower values of HR and low oxygen uptake were ascribed to the semistatic nature of muscle work performed during hiking that is in general isometric but also involves dynamic actions, which enables the sailor to sustain relatively high levels of effort over long time periods. The early heart rate and oxygen uptake data reported by Blackburn (1994) are not strictly in line with those of Cunningham & Hale (2007) who in a 30-min simulation protocol carried out in a dinghy ergometer, observed mean oxygen uptakes of 58% of VO_2max with heart rates of 150-160 beats*min^{-1} corresponding to ~84% of maxHR. The difference between these studies could be attributed to differences in the simulation task with respect to how dynamic the hiking movements were performed.

Combined with previous reports of actual on-water heart rates of up to 145-168 beats*min-1 during upwind hiking in the Laser (Pudenz, Dierck & Rieckert, 1981; Vogiatzis, Spurway, Wilson & Boreham, 1995) the data collectively support the notion that hiking in the Laser dinghy requires a more dynamic effort than what has previously been believed.

In an on-water race simulation for boardsailing Vogiatzis et al. (2002) measured heart rates of 87% and corresponding oxygen uptakes of 77% of VO_2max when measured over successive 4-min periods of sailing. Comparable or greater values for metabolic response have been observed in boardsailing by De Vito et al. (1996 & 1997), and more recently, Castagna et al. (2007; 2008) reported oxygen uptake values of 65 $ml*kg^{-1}*min^{-1}$, or above 80% of VO_2max, with heart rates above 90% of HRmax and serum lactate exceeding 10 $mmol*l^{-1}$ in elite Olympic board sailors when recorded during highly taxing conditions on water (characterized by light wind and down-wind sailing where immense sail pumping (i.e. manual repetitive movements with the rig) contributes as a main factor to propulsion). Taken together, it seems that Olympic boardsailing requires a high contribution of aerobic and anaerobic metabolism, and may in certain conditions and phases of the race be considered as physically demanding as e.g. bicycle racing or cross country running (De Vito et al. 1997; Vogiatzis et al. 2002). It should be noted however, that some yacht classes allow free pumping in specific wind conditions, and although to the authors knowledge, no physiological data exist on these sailors, it is likely that also very high values of VO_2 and HR may be anticipated under such conditions.

3.4 Fatigue

In recent decades Olympic sailing was dominated by long races (1-2 hrs) where sailors upheld quasi-static postures, which resulted in substantial metabolic stress accumulation in isometrically contracting muscles during long-term hiking. Previous studies have observed that hikers demonstrate superior abilities to sustain isometric contractions compared to non-hikers or controls (Larsson et al. 1996, Vangelakoudi et al. 2007), but on-water measures of muscular fatigue seem not to have been reported previously. A recent study on hiking fatigue performed on-water measurement of hiking strap forces during upwind sailing with full hiking (national level Europe dinghy sailors, n=9), and found 35% reduction in hiking strap forces after 10 min of sailing (Buchardt-Christiansen, 2013). The reduced production of force likely represents development of (neuro)muscular fatigue, and underscores the importance of the ability to sustain prolonged muscular contraction in elite sailors involved in hiking. Although hiking remains an important factor in Olympic sailing, the changes in yachts and regatta formats *per se* have introduced more dynamic sailing modes that to a greater extent exploits both aerobic and anaerobic energy processes. A very recent study illustrated the development of fatigue in international elite 49'er sailors by use of a race simulation (on land) that mimicked the theatre style racing format, which has been applied in this class: A simulation of 3 consecutive 5-min races that each included 6 maximal 'spinnaker pulls' resulted in an acute 26% reduction in peak power for this task (Fig. 4). Towards the end of the simulation race that also contained trapezing, trimming, tacking tasks etc. the sailors approached maximal heart rate values, underscoring that aerobic and anaerobic metabolism is highly involved in this type of sailing (Bay & Larsson, 2013).

insert Figure 4 appr here

4. Conclusions

In conclusion, the format of Olympic sailing has changed such that more dynamic yachts have been introduced, and the racing format includes briefer races with more frequent maneuvers. The consequence of these changes is that the number of hikers has decreased while the side hikers are no longer part of the Olympic format. The number of board sailors has remained constant more or less since the introduction, while the number of sailors in trapeze has increased substantially.

Present literature suggests that modern Olympic sail racing imposes substantial demands on the physical capabilities of the sailors. The demands for hikers and side hikers in general include very high levels of knee extensor muscle strength and high muscle endurance capacity, accompanied by medium to high aerobic capacity. The physical demands on the trapeze sailors are less well examined, however, in addition to great agility and balance skills, the requirements seem to involve large aerobic and even anaerobic capacity especially for the crewmen. Finally, board sailors seem to be exposed to the greatest physical demands, where conditions in some instances may tax the aerobic and anaerobic metabolism at maximal levels which means that boardsailing in intensity is comparable to endurance events like cycling, running or cross country skiing.

5. Perspectives/recommendations

Based on the above, it seems clear that additional studies are warranted to increase current knowledge about the physical requirements in Olympic sailing. Previously, accurate measurement has been limited by difficulties pertaining to the harsh sailing environment. However, recent advances in technology such as video, GPS, telemetrics and portable physiological measurement devices enables much more detailed study of sailing compared to what was previously possible. With present technology it is likely that additional steps can be taken in sailing science.

More specifically, recommendations for future investigation follows the recent developments in sailing as described above. For hikers and board sailors quite a few reports have been published and knowledge on the requirements for fitness and muscle strength in these groups is quite well described. But since the fraction of trapeze sailors in Olympic sailing has increased markedly, it seems that future research should focus on the physical requirements in the modern, more dynamic type of sailing. Requirements not only with respect to muscular strength and/or aerobic fitness in trapeze sailors should be examined, but the focus should also be on agility, precision and balance abilities in general, and combined into situations where the aerobic system is highly taxed. Moreover handling of the yachts is key to performance on short intensive courses, and thus detailed analysis of optimal/economic movement patterns in specific maneuvers should be investigated. A single previous study examined temporal patterns of physical activity in different Olympic classes during sailing (Legg, Mackie & Smith, 1999). That study mainly focused on hikers, but similar assessments are much needed for trapezing sailors and boardsailors.

Finally, the overall increase in the physical demands of Olympic sailing, and the change towards more dynamic actions in sailing also introduces an increasingly important aspect of fatigue, which in turn requires development of strategies for optimal restitution between consecutive races on one day, between race days, and between regattas within the season. Knowledge on optimal muscular restitution derived from other sports with similar repetitive and high intensity formats (e.g. sprint cross country skiing) could prove useful for athletes and coaches in Olympic sailing.

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Figure legends

Figure 1. Development in the categories of sailors in a full national Olympic team from 1968 to present. In recent years the percentage of trapezing sailors has increased, while hikers and side hikers have decreased.

Figure 2. Maximal isokinetic muscle strength (±SEM) of the knee extensors (quadriceps, closed symbols) and knee flexors (hamstrings, open symbols) in female national team sailors (A) and male national team (B), obtained in 2002 (triangles) and prior to 1992 Olympics (squares). Note the extreme values recorded for maximal quadriceps strength in the 2002 tests, especially during slow eccentric contraction. (figure from Bojsen-Møller et al. 2007, Journal of Sport Sciences, reprinted with permission).

Figure 3. ***Aerobic capacity (VO_2max) in Danish Olympic sailors through 25 years.*** Data are means +SD. Open bars represent female sailors and black bars are males. "Hikers" comprise Laser, Laser radial, Finn, Europe sailors and helmsmen in 470, Flying Dutchman , Star, Soling, Yngling and Tornado. "Sidehikers" are Star, Soling and Yngling crew. "Trapeze" are 49'er, 49FX and crew in Flying Dutchman, 470 and Tornado. "Board" are Lechner and RS:X. "Classic" denotes the more classic dinghy/yacht designs such as Finn, Laser, Laser Radial, Europe, Flying Dutchmann, Soling, Star, while "Skiff" denotes high performance dinghys 49 and 49FX. A large difference exists in number of sailors in each category (Hikers female n=24, male n=37; Sidehikers, female n=3, male=5; Trapeze female n=10, male n=38; Board female n=3, male n=9; Classic female n=31, male n=52, Skiff female n=6, male=28).

Figure 4. Peak power in repeated spinnaker pulls (mimicking spinnaker hoists/drops) during simulated high intensity racing performed in the laboratory. The study simulated three 5 min races separated by 5 min pauses. Eight elite 49'er crewmen participated, and on average peak power during spinnaker hoists were reduced by 26%. (Bay & Larsson 2013)

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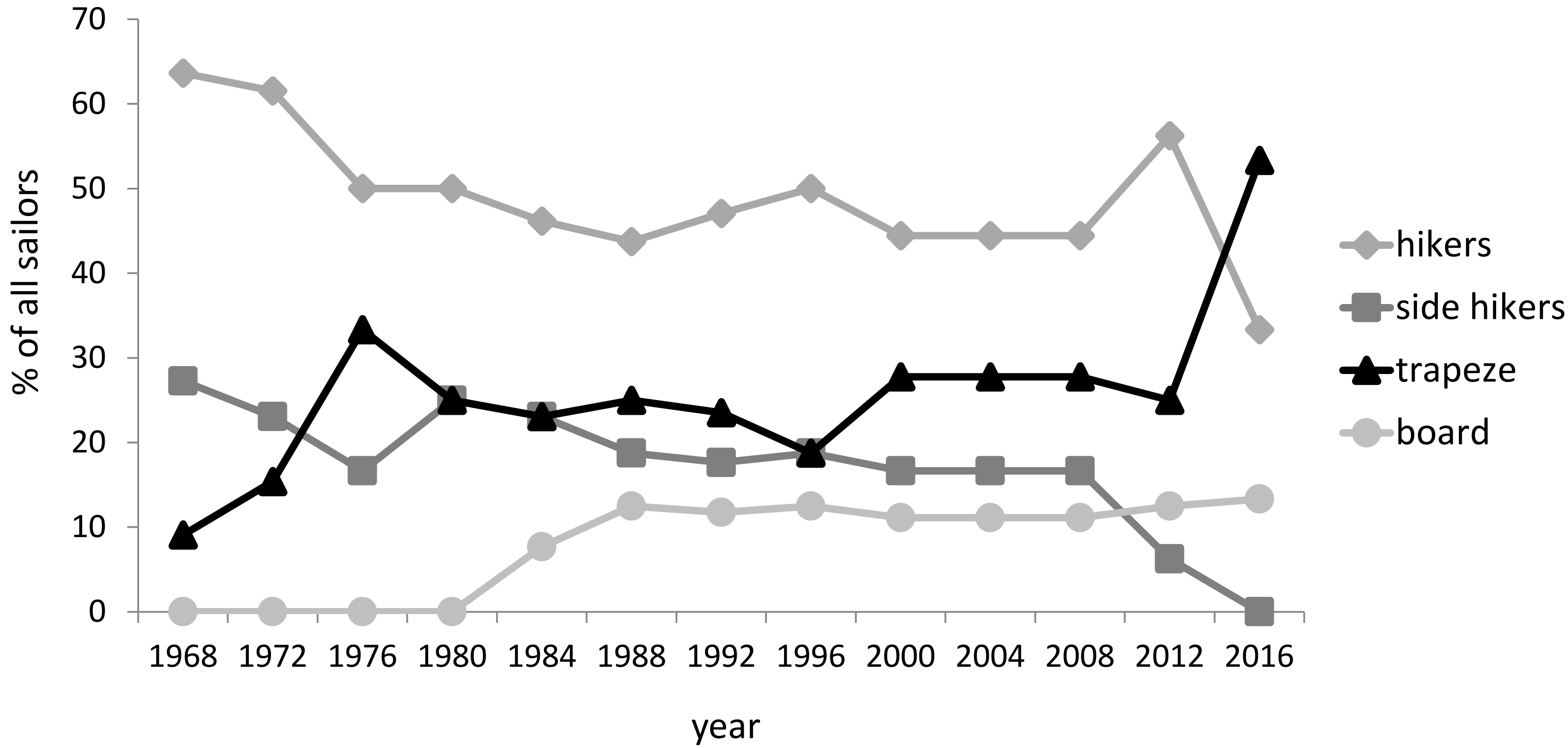
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Figure 1

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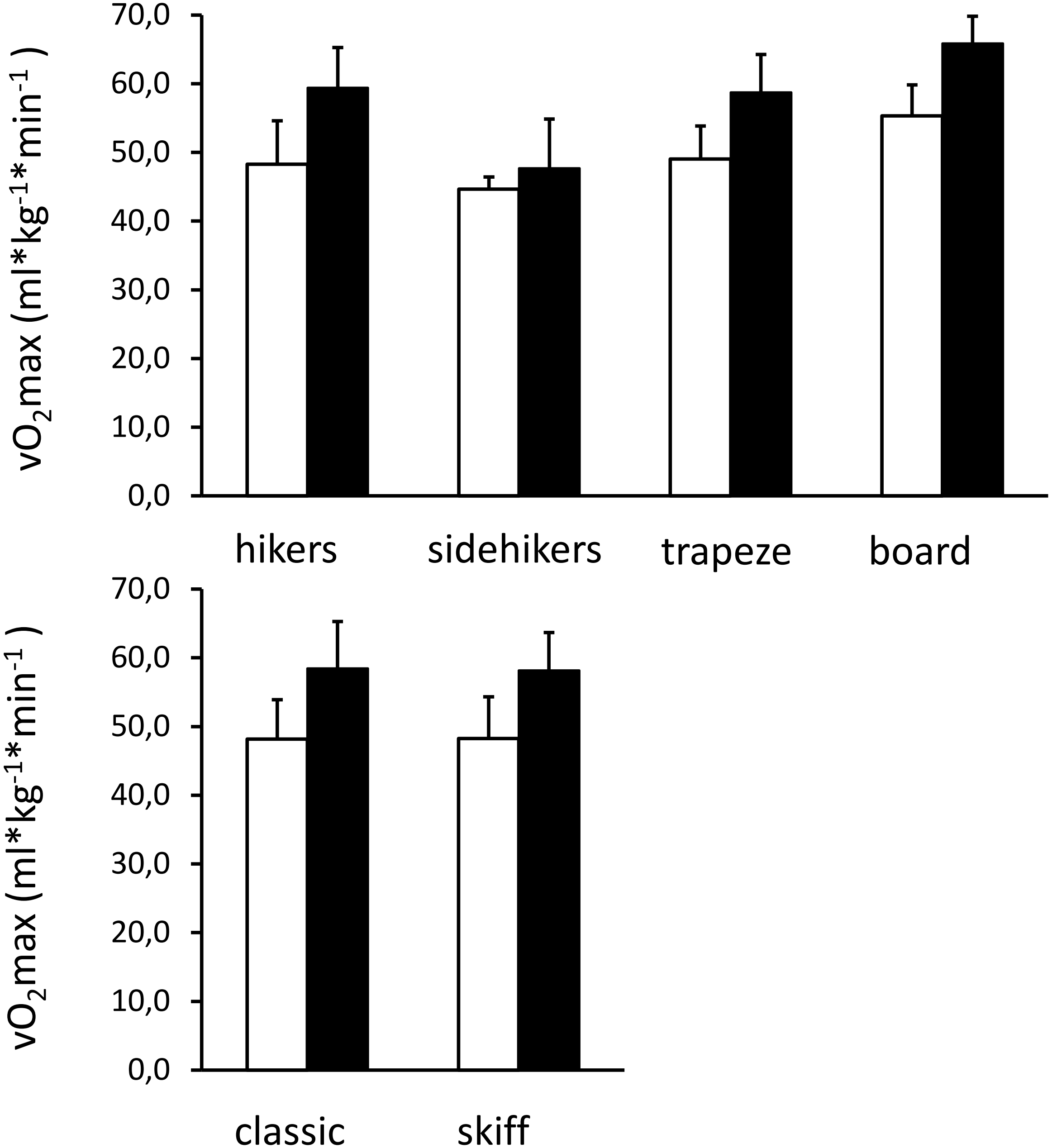
Figure 2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skiff

Figure 3

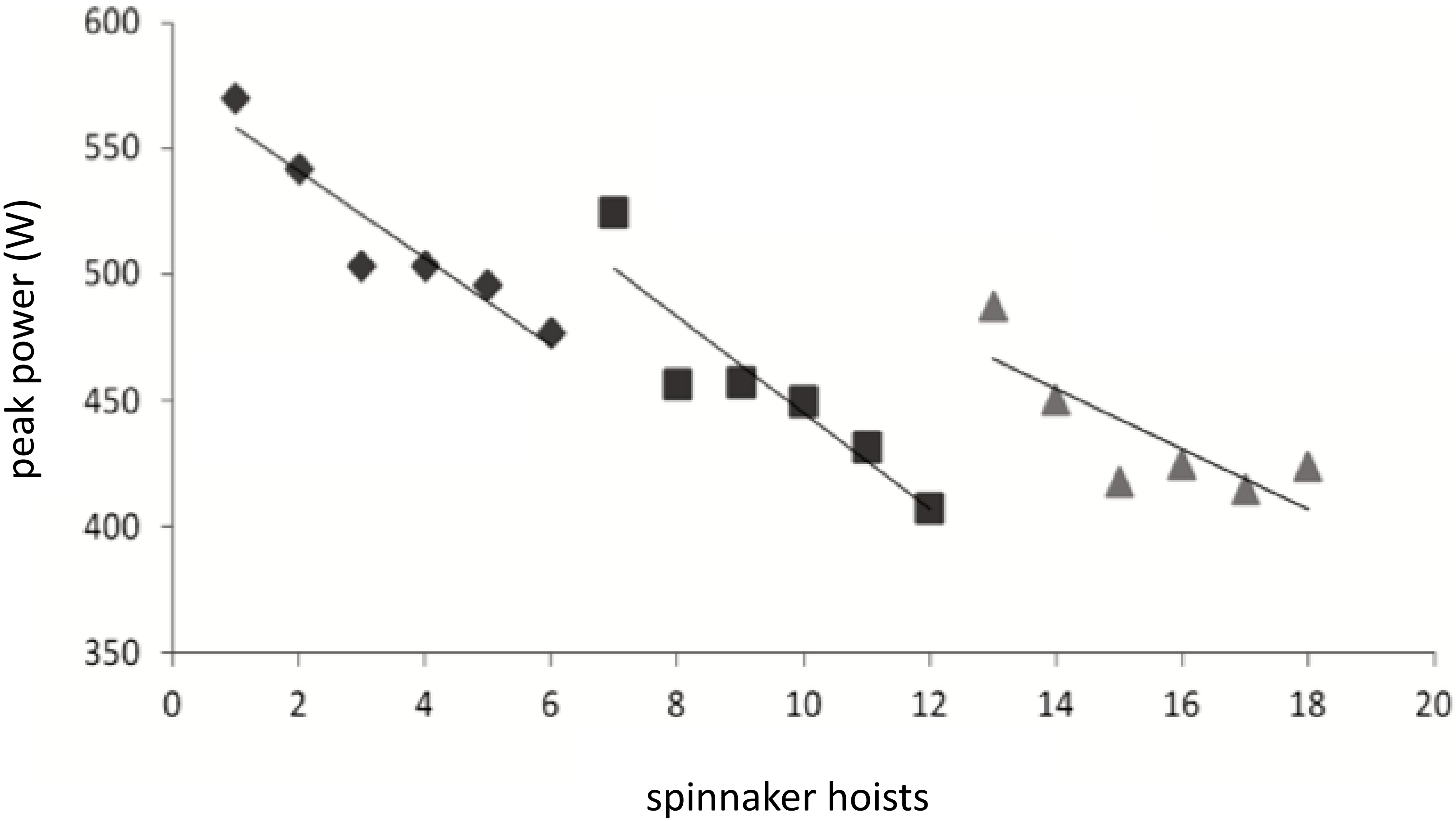
600
550
500
450
400
350
peak power (W)
0
2
4
6
8
10
12
14
16
18
20
spinnaker hoists

Figure 4