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REVIEW ARTICLE

Biomechanical and Physiological Demands of Kitesurfing and Epidemiology of Injury Among Kitesurfers

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Abstract Kitesurfing is a relatively new extreme water sport that is considered a high-risk sport and has rising popularity. Kitesurfing combines aspects of several water sports, including surfing, windsurfing, and wakeboarding. With a large controllable kite and a small board, kitesurfers travel over the water surface with speeds of up to 35 knots. The vertical lift of the kite makes it possible to perform jumps up to 15 m high and 30 m long, while doing different manoeuvres in the air. Few scientific data are available concerning the biomechanical and physiological demands of kitesurfing and the epidemiology of kitesurfing injury, and research methods used are often questionable. During kitesurfing, considerable stress is placed on the musculoskeletal and physiological systems, and the possibility of injury or fatality is an inherent part of participation. The lower back and thigh muscles are often perceived as being highly stressed, while abdominal muscles, knees, and feet are common sites of pain or discomfort. During kitesurfing, both aerobic and anaerobic metabolism contribute to energy delivery. It is reported in the literature that kitesurfing injuries are mainly acute, due to accidents or trauma. Non-competitive kitesurfing resulted in an overall injury rate of 5.9–7.0 injuries per 1,000 kitesurfing hours. It seems that the risk of injury increases dramatically in competitive kitesurfing. However, contradictory results have been found. Lower extremities were the most common major site of injuries, followed by upper extremities, trunk, and head. Most accidents during kitesurfing reported in the literature were attributed to the inability to detach the kite from the harness. Due to technical innovations, recent studies report uncontrolled actions and unsuccessful tricks and jumps with poor landings as the main mechanisms of injuries. The main purpose of the present paper is to critically analyse the current relevant scientific literature on the biomechanical and physiological demands of kitesurfing and the epidemiology of injury among kitesurfers, in order to obtain greater insights into (i) the stresses imposed on the musculoskeletal and physiological systems by kitesurfing, and (ii) the rate, pattern, and mechanisms of kitesurfing injuries.

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1 Introduction

High-risk sports are defined as activities where the possibility of injury or fatality is an inherent part of participation, and specialized equipment and training is generally required in order to minimize the risks involved [1]. Kitesurfing may be considered a high-risk sport, because of the potential for severe injuries and even death [2–8]. Although kites were developed for kitesurfing in the late 1970s and early 1980s, and a patented inflatable kite first appeared in 1984, the sport of kitesurfing is relatively new. Reported to be first performed in 1996, kitesurfing gained popularity very quickly and is now one of the fastest growing water sports. It is estimated that the number of kitesurfers worldwide is increasing every year by approximately 30 % [9, 10].

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Kitesurfers are defined as 'thrill and adventure seekers' from all age categories, and participants are mainly men who feel the need for varied, novel, and complex sensations and experiences in sport and leisure, and who have the willingness to take physical risks and the possible social consequences for the sake of such experiences [11, 12].

Kitesurfing combines aspects of several water sports, including surfing, windsurfing, and wakeboarding [13]. With a large controllable kite (5–20 m^2, at 20–25 m up in the air and a handlebar connected to the harness of the kitesurfer) and a small board (120–200 cm) with footpads and straps for comfortable riding, kitesurfers travel over the water surface at speeds of up to 35 knots. The vertical lift of the kite (hooked-in or unhooked: kite is attached or not attached to the harness, respectively) makes it possible to perform jumps up to 15 m high and 30 m long, while doing various tricks in the air. Crossing (sideways transportation over the surface of the water) and freestyle (jumps and pop tricks), both performed as recreational activities and as a competitive discipline, are the main elements in kitesurfing.

Scientific data concerning the mechanical and physiological stresses of kitesurfing and the rate, pattern, and mechanisms of kitesurfing injuries are scarce. Considerable stress is placed on the musculoskeletal and physiological systems [13–15], and the possibility of injury or fatality is an inherent part of participation [2–8, 12, 16, 17]. The methodology of these studies is often questioned. The specific characteristics of the participants, the very specific environmental circumstances, and the weather conditions all have an influence on the outcome, which is sometimes controversial and difficult to interpret. Furthermore, technical innovations in kitesurfing equipment and protective gear over the last decade have had an impact on results. The introduction of the 100 % depowerable kites and quick release systems in 2004–2005 was a milestone in kitesurfing safety [4].

In this context, an in-depth analysis of the current existing kitesurfing literature can be a first step to understanding the mechanical and physiological stresses imposed on kitesurfers and the epidemiology of injury among kitesurfers. Therefore, the objective of the present paper is to critically analyse the current relevant scientific literature on the biomechanical and physiological demands of kitesurfing and the epidemiology of injury among kitesurfers in order to obtain greater insights into (i) the stresses imposed on the musculoskeletal and physiological systems by kitesurfing, and (ii) the rate, pattern, and mechanisms of kitesurfing injuries.

2 Literature Search Methodology

The available scientific literature was consulted using a functional approach to identify (i) the movement pattern and mechanical and physiological stresses imposed during kitesurfing, and (ii) the rate, pattern, and mechanisms of injury among kitesurfers and their accompanying risk factors.

We undertook a systematic search in the Ghent University library and on the online databases PubMed, LibHub, Web of Science, and Compendex for international peer-reviewed research articles, selected conference proceedings, case reports, and reference lists of published research and review articles. The following search terms (and variants and combinations of these) were used: kitesurfing, physiology, biomechanics, movement pattern, accident, epidemiology, injury, rate, pattern, mechanism, safety, guideline, procedure, prevention, precaution, strategy and a combination of previous and related terms. Studies were limited to the English, French, and German languages. All publications identified by this means were reviewed and critically analysed for relevance to this project. Due to the scarcity of published literature, a search for additional relevant studies, papers, reports, dissertations, books, or book chapters (Google Scholar and Google) on kitesurfing, referenced in previously reviewed publications, was performed. Besides the English, French, and German language documents, sources in other languages that had been translated were also used. All documents were reviewed and critically analysed for (i) general content, (ii) purpose, (iii) methods used, (iv) results, and (v) conclusions. A document was only retained if all authors found it scientifically acceptable and relevant in the context of the purpose of this article. The whole literature research resulted in the identification of 17 papers, two master's dissertations, and one book chapter.

3 Findings

3.1 Biomechanical and Physiological Demands of Kitesurfing

Only three journal publications and one master's thesis on the biomechanical and physiological demands of kitesurfing could be identified. Nonetheless, understanding the movement patterns [15] and mechanical stresses [18], as well as analyzing the physiological demands, of kitesurfing [13, 14] can give a thorough insight into the determinants of kitesurfing and an individual's ability to practice kitesurfing without getting injured.

Based on task analysis (observation) and survey (questionnaire and interviews) studies, Lundgren et al. [15] provided an overview of the specific movement patterns in kitesurfing, distinguishing between crossing and freestyle. Kitesurfers' perceptions of musculoskeletal stress, pain, and discomfort were also identified. Crossing is characterized as sideways displacement (sometimes slightly upwind or downwind), where the kitesurfer (hooked-in) leans backwards to the water surface and performs mainly quasi-isometric (only small flexion/extension movements in hip and knee to compensate for small waves) contractions with forward rotation of the upper body. Due to hyperextension of the lumbar spine and the quasi-isometric contractions, the abdominal muscles (to counteract increased lumbar lordosis), the lower back, and thigh muscles were perceived as being highly stressed, especially in strong winds. Freestyle, or performing jumps with the kite, and pop tricks, using the lift of the kite, caused the kitesurfer (hooked-in or unhooked) to lift from the water. It is characterized by increased hip flexion before take-off, different body positions during air-time (extended body or certain parts flexed to spin or grab the board), and hip and knee joint extension before landing, and flexed while decelerating the body in a vertical direction. Abdominal muscles (recompose the body before landing), knees and feet (shock absorption), but also shoulders and elbows (especially when unhooked from harness) were often reported as the site of pain or discomfort when landing jumps at high speed [15].

Forced vibration is caused by the action of external forces and can create mechanical damage to human tissue as well as psychological stress. Valsecchi [18] quantified whole-body vibration exposure during kitesurfing, using triaxial and monoaxial accelerometry. More than 200 km of tests on four different locations were performed with a single kitesurfer and a kiteboard. The dominant vibration axis during kitesurfing was usually the *Z*-axis (foot to head average exposure value a_{wz} was 5.51 m.s^{-2}). Using a wave magnitude buoy, a cup anemometer, and a global positioning system (GPS), it was also found that, independent of location, vibration depended especially on the riding speed, whereas the effects of wave magnitude and wind speed seemed negligible.

Vercruyssen and co-workers [13] assessed the physiological demands of competitive kitesurfing during a 30-min on-water simulated crossing event in light wind (12–15 knots) conditions in ten highly competitive kitesurfers of national and international level [mean ± standard deviation (SD) age, height, weight, and maximum oxygen uptake (VO_2max), respectively, 30.3 ± 3.9 years, 177.0 ± 6.9 cm, 69.5 ± 9.5 kg, and 54.8 ± 3.3 mL·min^{-1}·kg^{-1}]. Indirect estimation of oxygen uptake (VO_2), based on heart rate (HR) measurements on the water and use of the HR–VO_2 relationship during a maximal progressive incremental running test, was used, and blood lactate ([La]$_b$) was measured. The mean ± SD sailing speed and covered distance during crossing were 21.0 ± 1.5 knots and 14,238 ± 973 m, respectively. Mean ± SD HR and VO_2 represented, respectively, 80.6 ± 7.5 % of maximum HR (HRmax) and 69.8 ± 11.7 % VO_2max, while the mean ± SD final [La]$_b$ was 2.1 ± 1.2 mmol·L^{-1}, indicating a mainly aerobic event of moderate intensity [13]. Using the same methodology, Camps and co-workers [14] organised a three times 7-min simulated freestyle event (60-min recovery between the events), with powerful and radical movements in medium wind (15–22 knots) conditions to assess the physiological demands of freestyle kitesurfing in ten competitive national and international kitesurfers (mean ± SD age, height, weight, and VO_2max, respectively, 22.2 ± 2.6 years, 175.6 ± 3.4 cm, 70.1 ± 2.5 kg, and 54.7 ± 1.5 mL·min^{-1}·kg^{-1}). Mean ± SD HR and VO_2 represented, respectively, 85.4 ± 3.0 % HRmax and 87.2 ± 4.3 % VO_2max, while mean ± SD final [La]$_b$ was 5.2 ± 0.8 mmol·L^{-1}, indicating an intense activity involving both aerobic and anaerobic metabolism. Vercruyssen et al. [13] found a significant relationship between the distance covered during the crossing trial and VO_2max values ($r = 0.83$; $p < 0.05$), while Camps et al. [14] observed significant relationships between % HRmax on water ($r = 0.764$; $p < 0.05$), estimated VO_2 on water ($r = 0.724$; $p < 0.05$), and the anaerobic threshold ($r = 0.836$; $p < 0.05$) on the one hand, and ranking position of freestyle kitesurfers on the other hand.

3.2 Rate, Pattern, and Mechanisms of Kitesurfing Injuries

Although the popularity of kitesurfing is rising, research on the rate, pattern, and mechanisms of kitesurfing injuries remains scarce. We found 15 publications on kitesurfing injuries: three prospective studies [7, 19, 20], six retrospective studies [3, 6, 8, 12, 16, 21], one cross-sectional online survey [22], three case reports [2, 4, 5], and two reviews [17, 23]. Study characteristics and results of all publications are summarized in Table 1.

Injury rate is based on the number of injuries and hours of sports participation over a certain period. In the following section, injury rate is reported as number of injuries per 1,000 kitesurfing hours. Prospective [7] and retrospective studies [6, 8] reported an overall injury rate of 5.9–7.0 injuries per 1,000 kitesurfing hours in non-competitive kitesurfing. However, a recent retrospective study (online questionnaire of 335 kitesurfers) [12] showed a clear increased injury rate of up to 12.2 injuries per 1,000 kitesurfing hours. Nickel et al. [7] found that the risk of injury increased dramatically in competitive kitesurfers from 6.8 injuries per 1,000 h during practice to 16.6 injuries per 1,000 h during competition. Pérez-Turpin et al. [16] performed a retrospective study on 38 elite kitesurfers (World Cup level). They found that injuries occurred more frequently when training than during competition (29

Table 1 Study characteristics and results of the 15 publications on kitesurfing injuries

Study	Participants	Study design	Duration of data collection	Total number of kitesurfing injuries (n)	Injury rate per 1,000 h of kitesurfing	Type of injury (%)	Anatomical location of injuries (%)	Sites and causes of injuries
Nickel et al. [7]	$n = 235$ (225 M, 10 F) Germany $M_{age} = 27.2$ years (14–48 years) $M_{exp} \pm SD = 2.8 \pm 0.2$ years Beg–Int–Adv–Exp	Prospective	6 months (2002) 17,728 kitesurfing hours 13,308 practice hours 420 competition hours	124	Overall = 7.0 Practice = 6.8 Competition = 16.6 Use of quick-release = 4.8 No use of quick-release = 7.6 Mild injuries = 5.4 Medium injuries = 1.4 Severe injuries = 0.2	77 mild 19 medium 3 severe 0.8 catastrophic	28 foot and ankle 14 head 13 thorax 13 knee	Sites: >50 m from the beach (54 %) <50 m from the beach (26 %) On the beach (20 %) Causes: overestimation of expertise ($n = 30$), misinterpretation of weather ($n = 19$), loss of control because of incorrect mounting ($n = 4$), technical mistakes ($n = 55$), mislanding jumps ($n = 38$), loss of control while crossing ($n = 13$), starting the kite ($n = 11$), board leash pulled kiteboard against head ($n = 8$), lines of the kite ($n = 5$), collisions with other kitesurfers or windsurfers ($n = 7$)
Exadaktylos et al. [19]	$n = 30$ (27 M, 3 F)	Prospective	7 months (2003–2004)	5	N.R.	Fractures, hypothermia, (severe) exhaustion, lacerations, and contusions	Fractures: humerus, ribs, and ankle Lacerations and contusions: head and neck region	N.R.
Berneira et al. [20]	$n = 50$ (47 M, 3 F) Brasil $M_{age} \pm SD = 30.7 \pm 7.9$ years $M_{exp} \pm SD = 4.2 \pm 2.7$ years	Prospective	2 months (2009)	73	N.R.	35.6 sprain 21.9 bruise 16.4 distension 6.8 fracture 6.8 laceration 2.7 dislocation 2.7 tendonitis 2.7 low back pain 4.1 others	50.7 lower limbs 28.8 upper limbs 20.5 head and thorax	Causes: Maneuver = 57.5 % Equipment = 15.1 % Maneuver and equipment = 13.7 % Being dragged = 5.5 % Other kitesurfers = 2.7 % Walking with the kite = 2.7 % Hit by a wave = 2.7 % Sun = 1.4 %

Table 1 continued

Study	Participants	Study design	Duration of data collection	Total number of kitesurfing injuries (n)	Injury rate per 1,000 h of kitesurfing	Type of injury (%)	Anatomical location of injuries (%)	Sites and causes of injuries
Turk et al. [3]	$n = 1$ Germany	Retrospective (autopsy-based study of 176 different sports-related fatalities)	10 years (1997–2006)	1	N.R.	Trauma	N.R.	N.R.
Petersen et al. [6]	$n = 72$ Non-competitive Germany	Retrospective	Season (2001)	31	Overall = 6.0 Medium = 1.0 Minor = 5.0	Direct trauma	N.R.	Causes: loss of control due to technical mistakes, oversized kites, onshore wind, and collisions
Lundgren et al. [15]	$n = 206$ (188 M, 17 F, 1 unknown) Competitive—recreational Worldwide Experience = 1–10 years Int level or better	Retrospective	2 months (2008)	251	Overall = 5.9 1–3 years of experience = 2.7	11.2 bone fracture 40.2 joint injury 18.7 muscle and tendon damage 5.6 internal bleeding 4.0 skull injury 14.3 wound and laceration 6.0 other	23.5 knee 17.3 foot and ankle 15.3 trunk 10.2 shoulders 8.2 arms 4.1 hip and thigh 4.1 head 1.0 neck 16.3 others and unknown	Causes: inadequate technical skills while doing jumps and tricks (40 %), environmental factors and tiredness (28.3 %), equipment (31.7 %)
Wegner and Wegener [12]	$n = 335$ (294 M, 41 F) $M_{age} \pm SD = 29.9 \pm 8.3$ years (14–55 years) $M_{exp} \pm SD = 2.83 \pm 0.7$ years Beg = 20.6 % Adv = 49.7 % Exp = 29.8 %	Retrospective	1 month (2009) 53,370 kitesurfing hours	653	Overall = 12.2 Beg = 30.9–16.6 Adv = 18.4–12.1 Exp = 10.4–6.1 Mild injuries = 10.0 Medium injuries = 1.9 Severe injuries = 0.4 Very severe injuries = 0.02	82 mild 15 medium 3.0 severe 0.2 very severe	N.R.	N.R.

Table 1 continued

Study	Participants	Study design	Duration of data collection	Total number of kitesurfing injuries (n)	Injury rate per 1,000 h of kitesurfing	Type of injury (%)	Anatomical location of injuries (%)	Sites and causes of injuries
Pérez-Turpin et al. [16]	n = 38 Age = 20–35 years Elite World Cup Fuerteventura 2008	Retrospective	12 months (2007–2008)	39	N.R.	Practice = 74.4 Competition = 25.6 Overall: acute = 76.3 vs. overuse = 23.7 (**) Overall: course race = 33.3 versus freestyle = 66.7 (**)	61 ankle 13 foot 11 knee 11 leg 5 shoulder	N.R.
Kwiatkowski [21]	n = 143 (132 M, 11 F) $M_{age} \pm SD = 29.1 \pm 8.1$ years Recreation—competition Worldwide Beg = 12.8 % Adv = 14.2 % Exp = 6.4 %	Retrospective	4 months (2003) 75,861 kitesurfing hours	74	Overall = 1.0 Mild injuries = 0.6 Medium injuries = 0.5 Severe injuries = 0.2	22.4 cuts 12.1 lacerations 10.3 bruises 10.3 fractures 8.6 abrasions 6.9 sprain and distortion 5.2 broken tooth 5.2 spine injury 3.4 eye injury 3.4 brain concussion 1.7 ear drum injury 1.7 ligament rupture	15 leg 13.3 foot 11.7 toes 10.0 knee joint 8.3 hip joint 8.3 elbow joint 8.3 finger 5.0 cervical spine 5.0 back 3.3 hand 3.3 thoracic spine 1.7 lumbar spine 1.7 ankle joint 1.7 arm 1.7 head 1.7 chest	N.R.
Pikora et al. [22]	n = 57 (48 M, 8 F, 1 missing) M_{age} = 34.2 years (17–58 years) M_{exp} = 3.6 years (0.2–10 years) Recreation—competition Australia Beg = 8.8 % Adv = 61.4 % Exp = 28.1 %	Cross-sectional online survey	12 months (2009)	52	Overall = 105	N.R.	N.R.	Causes: trying new tricks, attempting something beyond control and/or skill level (65 %)

Table 1 continued

Study	Participants	Study design	Duration of data collection	Total number of kitesurfing injuries (n)	Injury rate per 1,000 h of kitesurfing	Type of injury (%)	Anatomical location of injuries (%)	Sites and causes of injuries
Spanjersberg and Schipper [2]	$n = 5$ (5 M) The Netherlands	Case report	N.R.	5	N.A.	High-energy traumas (dislocation, laceration, fractures, amputation, cuts, paralysis, deformation of the maxillofacial area) and drowning	Case 1: shoulder, elbow, and patella Case 2: arm, hand, and leg Case 3: shoulder, femur, and face Case 4: chest Case 5: face and skull	Causes: collisions, falls from height and weather conditions
Ziegler et al. [4]	$n = 1$ (1 M)	Case report	N.R.	1	N.A.	Drowning	N.R.	N.R.
Scheibe et al. [5]	$n = 4$ (3 M, 1 F)	Case report	Case 1 and 2 (2007) Case 3 (2002) Case 4 (2004)	4	N.A.	Case 1: abrasions Case 2: blunt chest trauma, blunt abdominal trauma, fractures, cuts and abrasions Case 3 and 4: polytrauma resulting in death	Case 1: arm, shoulder, foot, elbow and hand Case 2: shoulder, elbow, thorax, abdomen and spine	Causes: Case 1: wind gust Case 2: wind gust Case 3: collision with other kitesurfers Case 4: collision with a boat and two flagpoles
Pikora et al. [17]	See Pikora et al. [22] See Nickel et al. [7]	Review	N.A.	N.A.	See Pikora et al. [22] = 1.1 See Nickel et al. [7]	See Pikora et al. [22]: N.R. See Nickel et al. [7]	See Pikora et al. [22]: N.R. See Nickel et al. [7]	See Pikora et al. [22] See Nickel et al. [7]
Petersen et al. [23]	See Nickel et al. [7] See Petersen et al. [6]	Review	N.A.	N.A.	See Nickel et al. [7] See Petersen et al. [6]	See Nickel et al. [7] See Petersen et al. [6]	See Nickel et al. [7] See Petersen et al. [6]: N.R.	See Nickel et al. [7] See Petersen et al. [6]

n number of, *M* male, *F* female, M_{age} mean age in years, *SD* standard deviation, M_{exp} mean experience in years, *Beg* beginner, *Int* intermediate, *Adv* advanced, *Exp* expert, *N.R.* data not reported, *N.A.* not applicable

** $p < 0.01$

injuries [76.3 %] versus 10 injuries [23.7 %]; $p < 0.01$) and that the course race category accounted for significantly more injuries than the freestyle category (26 injuries [66.7 %] vs. 13 injuries [33.3 %]; $p < 0.01$).

Lundgren et al. [8] observed significantly more injuries in less experienced kitesurfers, but a significantly lower injury rate (2.7 injuries per 1,000 kitesurfing hours) as compared with more experienced kitesurfers. Wegner and Wegener [12] also found that kitesurfing beginners (level 1 and 2) suffered injuries more often than experienced kitesurfers (advanced at level 3–4 and expert at level 5–6). However, in contrast with the results found by Lundgren et al. [8], these authors [12] observed a significantly higher injury rate (respectively, 30.9 and 19.6 injuries/1,000 h in level 1 and 2) in beginners than in advanced (respectively, 18.4 and 12.1 injuries/1,000 h in level 3 and 4) and expert (respectively, 10.4 and 6.1 injuries/1,000 h in level 5 and 6) kitesurfers, while more experienced kitesurfers (level 3, 4, 5, and 6) suffered from more severe injuries [12]. In a cross-sectional online survey (retrospective), Pikora et al. [22] reported in recreational kitesurfers an injury rate of 105.0 injuries/1,000 h of kitesurfing. However, in their review, the investigators reported an injury rate of only 1.1 injuries per 1,000 kitesurfing hours for the same population [17]. This injury rate is consistent with the results of Kwiatkowski [21] (retrospective design), indicating an injury rate of only 1.0 injuries per 1,000 kitesurfing hours in a very heterogeneous population of kitesurfers. Depending on study design, level of participants, and recreational activity or competitive discipline, a large range of injury rates were found.

According to Watson [24], Seil et al. [25], and Baltzer et al. [26], injuries leading to permanent disability or death are classified as catastrophic injuries, while injuries resulting in absence from sports participation for a period are classified as severe (>6 weeks absence), medium (>1 day absence), or mild (incapacity to train or compete on a normal basis). Petersen et al. [6] observed 31 accidents among 72 kitesurfers during one kitesurfing season. Five athletes had medium injuries (fractures: 1/1,000 h kitesurfing), while the others presented injuries where no medical treatment was needed (5/1,000 h kitesurfing). Nickel et al. [7] observed 124 injuries in 235 kitesurfers over a 6-month period. They [7] reported one fatal accident (polytrauma: 0.8 %; 0.05/1,000 h kitesurfing) and 11 severe injuries (3 %; 0.2/1,000 h kitesurfing). The majority of the injuries were classified as mild (77 %; 5.4/1,000 h kitesurfing) or medium (19 %; 1.4/1,000 h kitesurfing). Wegner and Wegener [12] observed 653 accidental injuries among a heterogeneous group (beginner, advanced, and expert level) of 335 kitesurfers over a 12-month period. Only 78 kitesurfers (23.3 %) had no injuries, indicating multiple injuries in some of the other 257 kitesurfers. They classified 533 injuries as mild (82 %; 10.0/1,000 h kitesurfing), 99 injuries as medium (15 %; 1.9/1,000 h kitesurfing), 20 injuries as severe (3 %; 0.4/1,000 h kitesurfing), and one injury as very severe (0.2 %; 0.02/1,000 h kitesurfing), which is comparable with Nickel et al. [7]. Pérez-Turpin et al. [16] observed 39 injuries in 38 elite kitesurfers over a 12-month period and classified injury severity in number of days of inactivity (abstain from training or competition for 1–3 days, 4–7 days, or 8–21 days). Injuries due to training seemed to be less severe than injuries during competition [1–3 days absence: 31 vs. 0 %; 4–7 days absence: 34.5 vs. 33.3 %; 8–21 days absence: 34.5 vs. 66.7 %; non-significant (ns)]. The course race discipline induced significantly more severe injuries during competition than the freestyle category (8–21 days absence: 36.8 vs. 30 % during training and 85.7 vs. 33.3 %; $p < 0.01$ during competition). Based on an analysis of kitesurfing-related offshore rescue missions in Cape Town (South Africa), Exadaktylos et al. [19] observed, over a period of 7 months, 30 air missions to rescue kitesurfers. Injuries occurred in five incidents, where two kitesurfers suffered from hypothermia and one experienced severe exhaustion. In a 10-year retrospective study on natural and traumatic sports-related fatalities in Hamburg (Germany), Turk et al. [3] identified one kitesurfing death caused by trauma. Kwiatkowski [21] reported 74 kitesurfing injuries among 143 kitesurfers over a period of 4 months, from which 20.6 % could be classified as severe. Lundgren et al. [8] and Berneira et al. [20] identified 251 injuries in 112 occasions when injuries occurred (3-month period) among 206 respondents (2.2 injuries for each occasion) and 73 injuries in 50 participants (2-month period), indicating multiple injuries in some athletes. This is in accordance with the observations of Nickel et al. [7] who reported 10.6 % of the 235 kitesurfers had multiple injuries (8.5 % had two injuries, 1.3 % had three injuries, and 0.8 % had four injuries over a 6 month-period). In the study of Pikora et al. [22], 52 % of their participants had one accident, 27 % two accidents, 14 % three accidents, and 6 % four accidents (12-month period). Case reports on kitesurfing injuries reveal, according to the former classification of Nickel et al. [7], two catastrophic injuries by drowning [4, 5] and six severe injuries [2, 4, 5].

A sports injury can be the result of a trauma or accident (acute) or of excessive loading over a short or long time, with tissue failure as a result (chronic). Kitesurfing injuries seem to be most often acute in nature (acute: 76.3 % vs. chronic: 23.7 %; $p < 0.01$) and no difference in the number of injuries is found between the right and left side of the body (right: 52.6 % vs. left: 47.4 %; ns) [16]. Of all injuries, 45–70 % occurred in the lower extremities [7, 8, 20, 21]. The ankle (64 %; $p < 0.01$) is the area of the lower extremities most affected by injury, followed by the foot

(14 %), the knee (11 %), and the lower leg (11 %) [16]. The upper extremities (18–22 %) were the second most common major site of injuries, followed by trunk (4–15 %) and head (2–14 %) injuries [7, 8, 21]. Joint sprain (up to 40 %); contusion (up to 34 %); abrasion (up to 28 %); muscle/tendon damage (up to 18 %); and wounds, laceration, and cuts (up to 17 %) were among the most frequent types of injuries, while fractures were responsible for 3–11 % of all injuries [7, 8, 20, 21].

Most accidents during kitesurfing reported in the literature were attributed to the inability to detach the kite from the harness. Control over the kite was lost, with collisions against rocks, boats, or other individuals being a common injury mechanism [2, 4–7, 19]. Petersen et al. [6] reported that most accidents occurred close to the beach due to technical mistakes, oversized kites, or bad wind conditions (e.g. an offshore wind or too much wind). In contrast, Nickel et al. [7] found that 54 % of all injuries occurred on the water at a distance >50 m from the beach, 26 % occurred on the water at a distance of <50 m from the beach, and 20 % of the injuries occurred at the beach while the kitesurfer was starting the kite. It should be noted that some of the data generated in these studies were collected before the introduction of the 100 % depowerable kites and quick release systems in 2004–2005 [4]. Recent studies reported uncontrolled actions (manoeuvres) [20] and unsuccessful tricks and jumps with poor landings [8, 22] as the main mechanisms of injuries. Lundgren et al. [8] noticed that 40 % of injuries occurred while performing jumps or tricks, with environmental factors and equipment affecting the extent of the injury in 74 % of cases.

4 Discussion

4.1 Biomechanical and Physiological Demands of Kitesurfing

Biomechanical and physiological analyses [13–15, 18] of kitesurfing suggest that considerable stress is placed on the musculoskeletal and physiological systems during crossing and freestyle. The lower back and thigh muscles were perceived as being highly stressed during crossing, while abdominal muscles, knees, and feet were the site of pain or discomfort during freestyle [15]. Quantification of whole-body vibration during kitesurfing (crossing) showed that the European Directive 2002/44/EC thresholds for whole body vibration [exposure action value (EAV) and exposure limit value (ELV)—minimum health and safety requirements regarding the exposure of workers to the risk arising from vibration] was reached after, 3 (EAV) and 15 (ELV) min, and seemed to depend primarily on the riding speed [18]. This suggests that, in the case of long exposure, or for people already exposed to whole-body vibration during their working activities, kitesurfing can trigger degenerative back pathologies [18]. Crossing can be considered as a moderately intense activity (65–70 % VO_2max) mainly sustained by aerobic metabolism [13], while freestyle can be evaluated as an intense activity (80–90 % VO_2max) where both aerobic and anaerobic metabolism contribute to energy delivery [14]. Intrinsic (e.g. sex, age, experience, physical fitness of the kitesurfer) and extrinsic (e.g. elements of kitesurfing, environmental circumstances such as wind force, wave height) factors can change those conclusions in various ways.

The studies related to the biomechanical and physiological demands of kitesurfing mentioned above often include methodological limitations: (i) use of observations, questionnaires and interviews to obtain information on the specific movement patterns and musculoskeletal stress, pain, and discomfort in kitesurfing, and (ii) a lack of actual oxygen uptake measurements on the water to measure the physiological demands of kitesurfing. Despite these limitations, it seems that a moderate to good level of general physical fitness (endurance, strength, velocity, flexibility, and coordination) is necessary to sustain the musculoskeletal and physiological stresses imposed, and these also seem to be a useful predictor of kitesurfing performance. This is confirmed when comparing the fitness of high-level kitesurfers with elite dinghy sailors and trained board sailors. VO_2max ($\approx$ 55 $mL \cdot min^{-1} \cdot kg^{-1}$) of kitesurfers [13, 14] is similar to that reported in elite laser sailors [27–30] but lower than that in trained board sailors (>60 $mL \cdot min^{-1} \cdot kg^{-1}$) [31–35]. The differences in VO_2max values between the kitesurfers and the board sailors can be related to the different nature of the muscle contraction. Kitesurfers and dinghy sailors have more isometric activation of upper and lower body muscles, while board sailors rely more on dynamic upper and lower body movements [13]. Therefore, general and specific physical training similar to that of dinghy sailors, in combination with intervention strategies to prevent injuries (proprioceptive exercises, core stability exercises, and articular mobilization before practice or competition), seems to be necessary to sustain and tolerate the moderate to high loads imposed on the musculoskeletal system, and to accommodate the physiological demands of kitesurfing.

4.2 Rate, Pattern, and Mechanisms of Kitesurfing Injuries

Since kitesurfing is often defined as a high-risk sport where the possibility of injury or fatality is an inherent part of participation, it is important to be acquainted with the rate and pattern of injuries, and to understand the mechanisms leading to injuries in kitesurfing in order to develop prevention strategies to avoid injuries. Prospective and retrospective studies on kitesurfing have estimated an overall injury rate of 5.9–7.0 injuries per 1,000 non-competitive kitesurfing hours [6–8]. However, the overall injury rate of 12 injuries per 1,000 kitesurfing hours, reported by Wegner and Wegener [12], is in contrast with previous data and showed a clear increase compared with earlier research results. The majority of the injuries were classified as mild (5.4–10.0/1,000 h kitesurfing) or moderate (1.4–1.9/1,000 h kitesurfing) [7, 12]. The overall injury rate in kitesurfing is comparable to that in snowboarding and recreational skiing (5.4 and 4.5 injuries/1,000 h respectively) [36, 37], and much higher than the injury rate seen with novice dinghy sailing (0.3 injuries/1,000 h of sailing) [38] and recreational boardsailing (0.2 injuries per 1,000 h of boardsailing) [39], but lower than professional rugby (69 injuries/1,000 h), college football (33 injuries/1,000 h), and men's college soccer (18.8 injuries/1,000 h) [40]. Injury rate more than doubled during kitesurfing competition (16.6 injuries per 1,000 kitesurfing hours) [7], which was somewhat higher than competitive surfing (13 injuries per 1,000 h of competitive surfing) [12]. More injuries, but a lower injury rate found in less experienced kitesurfers, was explained by the larger amount of time they spent practicing [8, 21]. However, Wegner and Wegener [12] observed a significantly higher injury rate in beginners than in advanced and expert kitesurfers. An injury prevalence of around 40 % was estimated [6–8, 22]. Kitesurfing seems to be a sport where injuries occur mostly in the lower extremities [7, 8, 16, 20, 21]. Kitesurfing injuries referred mainly to traumas or accidents due to collisions and were attributed to the inability to detach the kite from the harness when control over the kite was lost [2, 4–7, 19]. More recent studies reported uncontrolled jumps or tricks as the main mechanism of injuries [8, 20, 22].

The overall rate, pattern, and mechanisms of injuries in kitesurfing are influenced by research methods (prospective study, retrospective study, cross sectional survey, web-based questionnaire, printed questionnaire, definitions), characteristics of the participants (recreational vs. competitive kitesurfers, beginners vs. advanced kitesurfers, club member vs. non-member), environmental (geographical location, surrounding area, beach type, wave conditions, water temperature) and weather (sunny, cloudy, rainy, misty, wind direction, wind force) circumstances, and technical innovations. Retrospective studies are not the best choice for evaluating sport-specific injury rates. Subjects may not be able to accurately estimate the number of hours spent kitesurfing over the period of the study, resulting in somewhat uncertain calculations of the injury rate [7, 8]. Minor and mild injuries can be forgotten in retrospective studies, while severe injuries are often given as a reason for having stopped performing the sport [7]. The ability to gather data from a large cohort worldwide at a reasonable cost with a web-based questionnaire instead of with a printed form reduced the personal contact and influence of the researcher on the respondent and made it impossible to estimate the effects of non-response bias [8]. Further, if there was a response, an objective diagnosis of the injury was not always made; rather participants completed a questionnaire or a daily logbook in which they noted their injuries, either during the study or retrospectively. While Watson [24] and Nickel et al. [7] defined an injury as any damage to the body that resulted in incapacity to practise or compete normally, a standardized definition of injury was absent in most studies. Some researchers included all injuries in their study, not just severe, mild, or minor, but also 'little prangs', while other authors reported only severe accidents (death or polytrauma). Kitesurfing injuries reported in the earlier literature dealt mainly with traumas or accidents due to collision. However, a sports injury can also be a result of excessive short- or long-term loading, with tissue failure as a result [8, 18]. The skill level of the kitesurfer (recreational vs. competitive level, beginner vs. advanced) is not always mentioned in the studies. This makes a truly accurate estimation of rate, pattern, and mechanisms of injuries in kitesurfing practically impossible. It is therefore necessary to highlight the variation in methodology and definitions of injury used in the different studies to explain the often large variation in research results.

Technical innovations in kitesurfing equipment (e.g. depower lines) and advances in protective gear can influence injury rate [4]. Nickel and co-workers [7] reported, as early as 2004, a tendency for kitesurfers using a quick-release system to sustain fewer injuries than those without such a system. In 2011, Pikora et al. [22] mentioned the use of modern and safer kites by 95 % of kitesurfers, while Lundgren et al. [8] showed that 40 % of kitesurfers wear protective gear (helmet and impact vests). In this context, it is no surprise that other factors also determine injury rate and pattern. Today, it is accepted that the risk of injury during crossing appears to be low. However, during a freestyle session where landing is important, it is not unusual that injuries mainly occur in the lower extremities [8, 22].

5 Conclusion

High-risk sports are defined as activities where the possibility of injury or fatality is an inherent part of participation, and specialized equipment and training are generally required in order to minimize the risks involved [1]. Based on our critical analysis of the existing literature, there are arguments to identify kitesurfing as a new ‘high-risk sport’. The fact that trauma and death due to kitesurfing have been reported, and specialized equipment and training are generally required to minimize the risks involved, provides further support for this conclusion. However, it is necessary to mention that no activity is risk-free. Moreover, considering the limited experimental data and the methodological limitations of the studies on mechanical and physiological stresses imposed during kitesurfing as well as on rate, pattern, and mechanisms of injuries among kitesurfers, it is difficult to estimate the real danger and risks of kitesurfing.

Well conducted studies will be necessary to provide an objective insight into the mechanical and physiological stresses imposed and the real rate, pattern, and mechanisms of injuries in kitesurfing. Objective biomechanical and physiological measurements in the laboratory and on the water, and well designed studies on rate, pattern, and mechanisms of injuries, may optimize sports medical research in kitesurfing. The recommendations for injury definition and methodology of injury surveillance in sailing (injury definition, recurrent injury definition, injury severity definition, exposure definition, prospective study, injury diagnosis, classification of injuries by nature, reporting incidence of injury, classification of the severity of injuries) as proposed by Neville and Folland [41] can be used as a first step towards safer kitesurfing.

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