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ORIGINAL INVESTIGATION

## Development of an Upwind Sailing Ergometer

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**Purpose:** To develop a sailing ergometer that accurately simulates upwind sailing exercise. **Methods:** A sailing ergometer that measures roll moment accompanied by a biofeedback system that allows imposing a certain quasi-isometric upwind sailing protocol (ie, 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; ie, step protocol at 80 W + 40 W/3 min) and an upwind sailing test (UST). During both, heart rate (HR), oxygen uptake ( $\text{VO}_2$ ), ventilation ( $V_E$ ), respiratory-exchange ratio, and rating of perceived exertion were measured. During UST, also the difference between the required and produced hiking moment (HM) was calculated as error score (ES). HR,  $\text{VO}_2$ , 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. **Results:** An average HM of  $89.0\% \pm 2.2\% \text{HM}_{\text{max}}$  and an average ES of  $4.1\% \pm 1.8\% \text{HM}_{\text{max}}$  were found. Mean HR,  $\text{VO}_2$ , and  $V_E$  were, respectively,  $80\% \pm 4\% \text{HR}_{\text{peak}}$ ,  $39.5\% \pm 4.5\% \text{VO}_{2\text{peak}}$ , and  $30.3\% \pm 3.7\% V_{E\text{peak}}$ . 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. **Conclusions:** Results 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 follow-up.

**Keywords:** hiking moment, physiology, quasi-isometric, dinghy sailing

Over the last 20 years, researchers have experienced how difficult it is to define the physiological demands of sailing upwind on dinghies,<sup>1-6</sup> which is characterized by a body position known as “hiking.”<sup>1,6-8</sup> Some studies explored the physiological demands of upwind Laser sailing on water<sup>3-5,9,10</sup> and reported on average a heart rate (HR) of 60% to 80%  $\text{HR}_{\text{peak}}$ , an oxygen uptake ( $\text{VO}_2$ ) of 35% to 45%  $\text{VO}_{2\text{peak}}$ , a ventilation ( $V_E$ ) of 40 to 50 L/min, and a blood lactate concentration ([La]) of 2.0 to 3.5 mmol/L.<sup>3-5</sup> Other studies explored the biomechanical demands of upwind Laser sailing on water and showed on average a mainsheet load (MSL) of 100 N to 200 N, or 25% to 35%  $\text{MSL}_{\text{max}}$ , with peaks up to 90%  $\text{MSL}_{\text{max}}$ ,<sup>9,10</sup> and a hiking strap load (HSL) of 600 N to 750 N, or 60% to 90%  $\text{HSL}_{\text{max}}$ , with peaks exceeding 100%  $\text{HSL}_{\text{max}}$ . In the latter, note that  $\text{HSL}_{\text{max}}$  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%  $\text{HSL}_{\text{max}}$  could be observed.

Several research groups have developed different sailing ergometers.<sup>6,7,10-14</sup> However, all those ergometers

implemented isometric exercise. In contrast, this study sought to impose a quasi-isometric upwind sailing protocol (ie, an emulation) to accurately simulate real upwind sailing exercise. The novelty of this upwind sailing ergometer's construction is that it allows the researcher to impose a certain quasi-isometric upwind sailing protocol (whereby the researcher defines the exact sailing conditions; ie, an emulation) to several subjects or to 1 subject on different occasions. Moreover, this ergometer enables researchers to conduct both profound physiological and biomechanical sport-specific research that includes complex recordings that are not waterproof and need careful assistance and follow-up from the researchers. In addition, this ergometer allows tracking of error score (ES), which is the difference between the required and produced hiking moment (HM), as an indicator of hiking precision.

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 hydrodynamic and aerodynamic point of view. An emulation means that the ergometer imposes a certain protocol on the sailor, but this protocol cannot be manipulated by the sailor's movements, in contrast to a simulation. Therefore, this ergometer is (from an engineering point of view) an upwind sailing emulation ergometer and not an upwind sailing simulator.

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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 was hypothesized that this ergometer would demonstrate physiological and biomechanical responses to upwind sailing exercise that are largely comparable to those reported during on-water upwind sailing. Moreover, it was thought that the sailors' feedback regarding the resemblance between the simulated and on-water sailing exercise would be positive.

## Methods

### Subjects

Ten male national-squad youth sailors (Laser radial), all members of the Flemish "Be Gold" talent team ( $\pm 150$  sailing d/y), 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) to exhaustion and an upwind sailing test (UST) within a period of 2 weeks to ensure that their level of physical fitness had not changed substantially. The subjects were asked to abstain from strenuous exercise for at least 48 hours before both of their visits to the laboratory.

The subjects' height (anthropometer GPM, DKSH Switzerland), body mass (Electronic Seca scale), and 10 skinfolds (Harpenden skinfold caliper) were measured. Percentage body fat was calculated by the method of Parizková.<sup>15</sup> The subjects' training history (ie, training volume, total sailing experience, and Laser sailing experience) was also questioned (Table 1).

### 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 2 roller bearings (in the longitudinal symmetry plane of the boat) and a force dynamometer. The latter restrains the roll motion of the hull on the port side 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

**Table 1** Subjects' (N = 10) Anthropometry, Training History, and Incremental-Cycling-Exercise Data, Mean  $\pm$  SD

Measure	Value
Anthropometry	
age (y)	18.5 $\pm$ 2.0
height (cm)	180.9 $\pm$ 4.7
body mass (kg)	72.3 $\pm$ 4.8
percentage body fat (%)	13.8 $\pm$ 3.0
Training history	
training volume (h/wk)	13.4 $\pm$ 5.1
sailing experience (y)	9.7 $\pm$ 2.5
Laser experience (y)	2.9 $\pm$ 1.3
Incremental-cycling-exercise data	
peak power output (W)	336 $\pm$ 33
VO <sub>2peak</sub> (mL $\cdot$ min <sup>-1</sup> $\cdot$ kg <sup>-1</sup> )	57.1 $\pm$ 4.2
V <sub>Epeak</sub> (L/min)	143 $\pm$ 24
RER <sub>peak</sub>	1.17 $\pm$ 0.04
HR <sub>peak</sub> (beats/min)	199 $\pm$ 9
[La] <sub>peak</sub> (mmol/L)	11.6 $\pm$ 1.5
power output at AT <sub>4</sub> (W)	248 $\pm$ 35
VO <sub>2</sub> at AT <sub>4</sub> (%VO <sub>2peak</sub> )	82.8 $\pm$ 5.7
HR at AT <sub>4</sub> (beats/min)	179 $\pm$ 9

Abbreviations: VO<sub>2</sub>, oxygen uptake; V<sub>E</sub>, ventilation; RER, respiratory-exchange ratio; HR, heart rate; [La], blood lactate concentration; AT<sub>4</sub>, theoretical anaerobic 4-mmol/L threshold.

straps were kept on the boat. Rudder and mainsheet 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 that investigated the load on rudder and mainsheet). On the tiller, an elasticized rope provides a resistance of about 15 N,<sup>7</sup> and a 10-mm shock cord<sup>14</sup> was used to apply a 120-N resistance on the mainsheet.<sup>10</sup> This resistance was validated by using weight calibration.

### Experimental Design

**ICT.** Each subject performed an ICT (ie, step protocol) on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands). The work rate increased stepwise with a rate of 40 W per 3 minutes. The actual step increase was preceded by 3 minutes of rest on the cycle ergometer and by 3 minutes of baseline cycling at 80 W.<sup>16</sup> The instantaneous pedal rate (65–70 rpm<sup>16</sup>) was continuously visualized on a display connected to the electromagnetic cycle ergometer, so that the subjects were informed about their cadence throughout the exercise test. The test was terminated when the subject could no longer maintain the instructed

pedal rate, despite strong verbal encouragement. The duration of the ICT was on average  $21 \pm 2$  minutes.

**UST.** The aim of the UST 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-second 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 HM. The peak HM was determined as the maximal static HM ( $HM_{max}$ ). The required HM ( $HM_{required}$ ) was always calculated as a percentage of the  $HM_{max}$ .

The upwind sailing protocol consists of 18 bouts of 90-second hiking at constantly varying HM interspersed with 10 seconds to tack. The variance in  $HM_{required}$  that has to be induced by the subject on the dinghy by means of hiking is a function that is a summation of the main function ( $HM_{main}$ ) and a varying function.  $HM_{main}$  varies constantly by means of a predefined function that consists of 5 seconds decreasing from peak hiking after the tack, 30 seconds of light hiking, 25 seconds of average hiking, 20 seconds of hard hiking, and 10 seconds of increasing hiking up to a dynamic peak value for the HM 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 made before and after every tack 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 to recover and delay fatigue as a result of the high hiking effort. In addition, the first and last bouts are different in hiking intensity than the rest of the bouts. The first bout consists of 60 seconds maximal hiking and

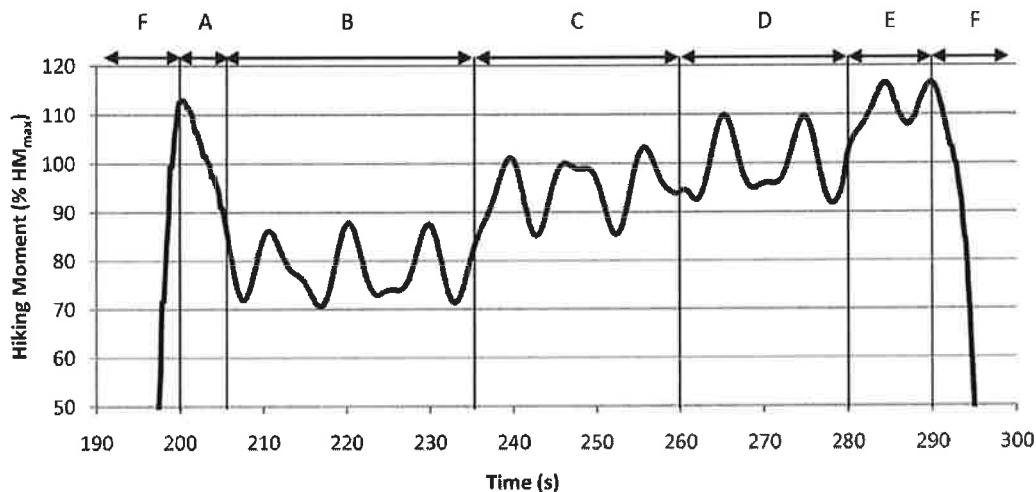
30 seconds hard hiking to represent the great hiking effort that is made to immediately take the lead of the fleet. The last bout consists of a higher hiking effort (ie, 10 seconds maximal hiking, 30 seconds average hiking, 20 seconds hard hiking, and 30 seconds maximal hiking) to represent the effort sailors make to fetch the mark as fast as possible.

Throughout the protocol, a constant varying signal is added to the previously described main function to represent the constant changes in moment on a real Laser dinghy (due to wind shift, waves, etc). This signal from the  $HM_{required}$  is described as  $HM_{main} + \delta HM \sin [(2\pi/T) \times t]$ , where  $\delta HM$  = 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).

To indicate the  $HM_{required}$ , 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, an anticipation system, and a synchronized upwind sailing video (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 center of the bicolored beam. Second, an anticipation system indicates whether the hiking would increase or decrease (or tack). Third, a synchronized upwind sailing video (with ambient sound) is shown in the corner of the screen to make the emulation more lifelike. This video is assembled from regatta recordings from national Laser sailors.

## Measurements

During the ICT,  $VO_2$ ,  $V_E$ , and respiratory-exchange ratio (RER) were measured continuously on a breath-by-breath basis using a computerized  $O_2$ - $CO_2$  analyzer-flowmeter



**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.



**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 or 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.

combination and averaged during 10-second intervals (Jaeger Oxycon Pro, Höchberg, Germany).<sup>16</sup> Before each test, the gas analyzers and volume transducer were calibrated. 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 [La] (Analox GM7; Analox Instruments Ltd, London, UK). Peak power output,  $VO_{2peak}$ ,  $V_{Epeak}$ ,  $RER_{peak}$ , and  $HR_{peak}$  were determined as the highest during an interval of 30 seconds<sup>16</sup> when at least 1 of the following criteria<sup>17</sup> was met:  $VO_2$  leveling off,  $RER > 1.10$ ,  $HR >$  theoretical predicted maximal heart rate ( $[220 - \text{age}] \pm 10$  beats/min), or  $[La] > 8$  mmol/L.  $[La]_{peak}$  was determined for every subject as the highest value seen throughout the protocol. For each subject, the theoretical anaerobic 4-mmol/L threshold ( $AT_4$ ) was determined. Power output,  $VO_2$ , and HR at  $AT_4$  were determined. The results from the ICT are displayed in Table 1.

During the UST, HM, HR,  $VO_2$ ,  $V_E$ , RER, and rating 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 Hz. HR was determined at rest and at the end of each hiking bout (ie, while the 10 seconds maximal hiking) by Polar RS400. Whole-body  $VO_2$ ,  $V_E$ , and RER were measured continuously every 10 seconds with the Acertys Jaeger Oxycon pro. RPE was measured by a 6-to-20 Borg scale.<sup>18</sup>

After the UST, the sailors were asked to evaluate the resemblance between the UST and on-water upwind sailing.<sup>8,19</sup> 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, and mainsheet

load). For this, a Likert scale (1 = very bad, 2 = bad, 3 = moderate, 4 = good, 5 = very good)<sup>19</sup> was used. Afterward, the researcher briefly asked each subject to clarify his opinion and noted down his remarks on the ergometer.

### Data Analysis

The HM is the average hiking load per bout (ie, during each 90-s hiking period) and is expressed as a percentage of  $HM_{max}$ . Moreover, the resultant of the  $HM_{required}$  minus the HM produced by the subject was calculated and expressed as ES. An average ES per bout (ie, 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 is lower than the  $HM_{required}$ .  $HR$ ,  $VO_2$ , and  $V_E$  were presented as relative values to, respectively, their  $HR_{peak}$ ,  $VO_{2peak}$ , and  $V_{Epeak}$ .  $HR$ ,  $VO_2$ ,  $V_E$ , and RER were calculated as an average value per bout (ie, during each 90-s hiking period).

### Statistical Analysis

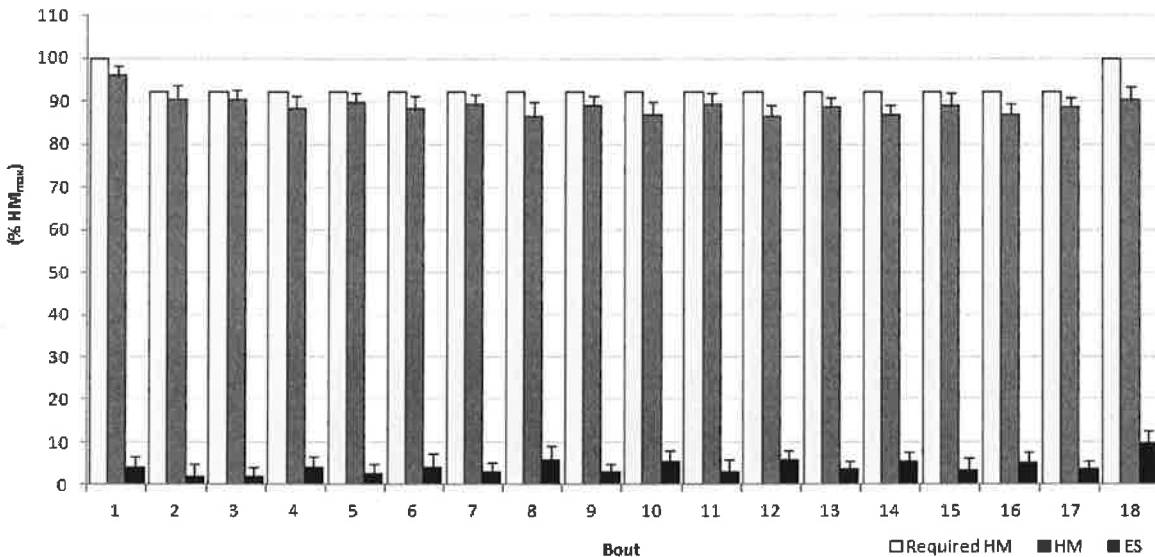
Statistical computations were performed using SPSS software (version 18; SPSS Lead Technologies Inc, Chicago, IL, USA). All data are presented as means (from all bouts)  $\pm$  SD. Repeated-measures ANOVA was conducted to investigate whether significant changes in ES,  $HR$ ,  $VO_2$ ,  $V_E$ , RER, 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 bouts 1, 4, 8, 12, 16, and 18. In contrast, repeated-measures analysis for ES was conducted with the values from bouts 2, 4, 6, 8, 10, 12, 14, and 16. Note that bouts 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  $HM_{required}$  during the first and last bouts (based on preliminary research before the beginning of these experiments). When a significant main effect was detected, 1-on-1 post hoc comparisons, followed by a Bonferroni-type adjustment, were conducted.<sup>20</sup> Statistical significance for all analyses was set at  $P < .05$ .

## Results

Table 1 demonstrates that the population is youthful ( $18.5 \pm 2.0$  y) but already has great sailing experience ( $9.7 \pm 2.5$  y) and is well trained both on and off water ( $\pm 150$  sailing d/y and  $13.4 \pm 5.1$  h dry-land training per week). Both their  $VO_{2peak}$  ( $57.1 \pm 4.2$  mL  $\cdot$  min<sup>-1</sup>  $\cdot$  kg<sup>-1</sup>) and maximal power output ( $336 \pm 33$  W), obtained during the ICT, turn out to be well developed.

Figure 3 shows the progress of both the required and the produced HMs and the difference between them expressed as ES. The ES is on average  $4.1\% \pm 1.8\%$   $HM_{max}$  (Table 2), and repeated-measures ANOVA shows no significant changes in ES over time, first and last bouts not included.  $HR$  significantly increased throughout the protocol ( $P < .001$ ,  $F = 16.713$ ). It sharply increased immediately after exercise onset and leveled off very fast (ie, only bout 1 differed significantly from bouts 4, 8, 12, 16, and 18). In addition,  $VO_2$  and  $V_E$  significantly increased ( $P < .001$ ,  $F = 61.073$  and  $P < .001$ ,  $F = 37.094$ , respectively; Table 2) throughout the 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 (ie, only bout 1 differed significantly from bouts 4, 8, 12, 16, and 18). Moreover, the RPE also increased significantly throughout the protocol ( $P <$



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

**Table 2 Measures During 18 Bouts of 90-s Hiking, Mean  $\pm$  SD**

Measure	Value
Hiking moment (% of maximum)	89.0 $\pm$ 2.2
Error score (% of maximum)	4.1 $\pm$ 1.8
Heart rate (% of peak)	80 $\pm$ 4
Oxygen uptake (% of peak)	39.5 $\pm$ 4.5
Ventilation (% of peak)	30.3 $\pm$ 3.7
Respiratory-exchange ratio	0.92 $\pm$ 0.02
Rating of perceived exertion	16 $\pm$ 2

.001,  $F = 72.888$ ). Post hoc analysis showed a significant increase up until bout 8, a leveling off until bout 16, and a significant increase from bout 16 until bout 18. In contrast, RER showed no significant change throughout the protocol.

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 the starting procedure ( $4.2 \pm 0.6$ ), hiking position ( $4.0 \pm 0.8$ ), variation in hiking intensity ( $4.0 \pm 0.8$ ), rudder load ( $4.3 \pm 0.8$ ) and MSL ( $4.6 \pm 0.7$ ). A moderate resemblance score could be seen for fatigue development ( $3.0 \pm 0.5$ ) and tacking procedure ( $2.5 \pm 1.0$ ), and a bad score was reported for boat tilt ( $1.7 \pm 0.7$ ).

## Discussion

The purpose of the current 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 a sailor on the boat, accompanied by a biofeedback system that allows imposing a certain quasi-isometric hiking protocol. The major findings of this study indicated a great similarity between the physiological and biomechanical outcomes 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 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. The ergometer allows imposition of a certain quasi-isometric upwind sailing protocol (based on unpublished preliminary on-water research) to accurately simulate upwind sailing exercise. It is important to note that the present measuring frame is from a hydrodynamic 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.

To express quantitatively how accurate the sailors performed the required HM, the difference between the  $HM_{\text{required}}$  and the HM produced by the sailor was calculated and expressed as ES. It was demonstrated that the ES does not increase throughout protocol. As such, the overall average ES could be calculated as  $4.1\% \pm 1.8\% HM_{\text{max}}$  (Table 2). Considering comparable results in the literature on isometric and isokinetic knee-extension force-control variability at 60% MVC during short periods (ie,  $\leq 15$  s)<sup>21</sup> and taking into account that we are dealing with a man-machine system that requires athletes 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 to improve its velocity.

The mean HM during each bout was  $89.0\% \pm 2.2\% HM_{\text{max}}$ , with peaks up to  $100\% HM_{\text{max}}$  (Table 2). This HM percentage is comparable to the literature reports on HSL during on-water research<sup>9,10</sup> (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 HR,  $VO_2$ , and  $V_E$ . 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 ( $80\% \pm 4\% HR_{\text{peak}}$ ),  $VO_2$  ( $39.5\% \pm 4.5\% VO_{2\text{peak}}$ , or  $22.5 \pm 2.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ), and  $V_E$  ( $30.3\% \pm 3.7\% V_{E\text{peak}}$ , or  $42.8 \pm 5.0 \text{ L/min}$ ; Table 2) measured during this UST match the on-water research reports<sup>3-5</sup> (Table 3). In this context, however, it should be argued that the  $VO_{2\text{peak}}$  obtained from the ICT in the current study, slightly underestimates actual  $VO_{2\text{max}}$ . In our study, the ICT lasted on average  $21 \pm 2$  minutes, whereas Buchfuhrer et al<sup>22</sup> showed that a test duration of 8 to 17 minutes is recommended to obtain  $VO_{2\text{max}}$ . Therefore, it can be suggested that the  $VO_2$ , expressed in  $\%VO_{2\text{peak}}$ , during the UST is slightly overestimated, so 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 the impossibility of real sailing (eg, unfavorable weather conditions) or for specific kicking training with simultaneous measures.

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 MSL. 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 dynamic movements they make on water. In addition, 2 subjects noticed that the upwind leg in a regatta is shorter than

**Table 3 Summary of Literature Reports From on-Water Measurements of Average Hiking Strap Load (HSL), Heart Rate (HR), Oxygen Uptake (VO<sub>2</sub>), and Ventilation (V<sub>E</sub>) During on-Water Sailing Upwind**

Ref	HSL (% of maximum)	HR (% of peak)	VO <sub>2</sub> (% of peak)	V <sub>E</sub> (L/min)	Situation
9	59%, peaks to 77%				On-water upwind sailing
8	87%, peaks >100%				On-water upwind sailing
3		74 ± 11	39 ± 6		10 min continuous upwind sailing
4		69.3	42.5	49.8	30 min sailing parcours
5		64.3	42.5	42.8	30 min continuous upwind sailing

during this UST, and 4 subjects reported that the tacking procedure was too slow compared with on-water tacking. Even so, 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<sup>23</sup> demonstrated that tacking lasted 4 to 9 seconds. In addition, other simulation studies frequently used a tacking period of 5 seconds.<sup>24,25</sup> However, due to practical issues (ie, safety care for the measurement instruments), we chose to use a 10-second tacking period.

The results of this study suggest that this ergometer creates a good representation of on-water upwind sailing. 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 would be done by converting the present measuring frame—from a hydrodynamic and aerodynamic point of view, 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 also study 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 a sport-specific training and evaluation tool (ie, to measure physical adaptation in sailing before and after training periods). The main reasons the ergometer is equipped with a Laser dinghy are 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 who 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 of the subjects. As such, it is suggested that this ergometer

could be a great help as an evaluation and sport-specific training tool in performance diagnostics and follow-up of the training process.

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