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Validation of a novel instrumentation (FlexOmega system) measuring oar bending moments on-water in rowing

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ABSTRACT

Quantifying rowing performance can facilitate control of training load or assessment of skill level. Accordingly, the FlexOmega system was developed, which records the bending moment of the oar. This work aimed to validate this new instrumentation during a dynamic load case. Two force profiles were first derived from bending moments acquired during on-water rowing (one at race pace, one at training pace). These force profiles were then used to repeatedly load the instrumented oar on a newly developed test bench. To ultimately elaborate how precision and accuracy determined on the test bench affects everyday training, i.e., whether practitioners can reasonably use the FlexOmega system, the measurement variability observed on the test bench was related to the measurement variability seen for on-water measurements.

On the test bench (featuring a mean precision of 99% and mean accuracy of 95%), a mean error of 3 Nm (mean precision: 98%, mean accuracy: 97%) was determined for the FlexOmega system for the force profile A characterised by bending moments of up to 300 Nm (racing simulated, 37 strokes per minute). For the force profile B with lower stroke rate and less force (21 strokes per minute, up to 150 Nm), the mean error was 2 Nm (mean precision: 98%, mean accuracy: 97%).

The measurement variability observed on the test bench was on average for the two force profiles 30% (profile A) and 15% (profile B) of the measurement variability that occurred during on-water rowing. We conclude that improving the measurement characteristics of the instrumentation would hardly result

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in any practical benefit as on-water measurements seem mainly to be influenced by the rower's skill level and environmental condition. Thus, the FlexOmega system can be used to control training intensity or to evaluate rowing performance. In addition, the presented approach for elaborating measurement characteristics could contribute to.

Keywords

dynamic loading, force profile, measurement variability, oar bending moment, test bench

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Introduction

As simple as the goal of a rowing competition may seem – to row 2,000 m in the shortest possible time – the underlying human movement execution is complex: different muscle groups distributed over the entire body must be coordinated and adjusted to the movement of the boat (and to the teammates, if any). As rowing has always been a discipline of the modern Olympic Games, rowing techniques and training measures have been extensively explored and summarised in various books that appeal to laymen and experts alike (e.g., Altenburg et al., 2008; Kleshnev, 2020; Nolte, 2011).

Theoretical knowledge about a supposedly ideal movement execution forms a basis for high performance. However, for purposive training it is important to assess the movement execution to evaluate the success of training measures or to adapt the training. Hereby, a key area for performance assessment is the force application at the oar (Warmenhoven et al., 2018). Coaches can indirectly assess the quality of the rower's overall applied forces based on their experience, for instance by observing boat or water behaviour. In addition, various instrumentations have been used to quantify the force transmission per oar. Measurements with such instrumentations have revealed, for example, that rowers adapt their force application to their teammates (Baudouin & Hawkins, 2004). If, in addition, these instrumentations provide the rowers with immediate information on their applied forces, rowers are better able to adhere to the intended training intensity than if they only rely on their own perception or on feedback from coaches (Lintmeijer et al., 2019).

In recent decades, rowing-specific performance analysis using a rowing ergometer has been established (T. B. Smith & Hopkins, 2012; Soper & Hume, 2004). Accordingly, various studies have reported on the reliability and validity of measurements with rowing ergometers (recently summarised by Held et al., 2022). However, despite the benefits of standardised analyses of individual rowers in the absence of environmental conditions, rowing ergometers do not adequately represent on-water rowing skills (T. B. Smith & Hopkins, 2012). For on-water measurements of rowing kinetic variables, various research groups have therefore instrumented the foot-stretcher (e.g., Baca et al., 2006; Krumm et al., 2010), the oar shaft (e.g., Castro et al., 2022; Hill, 2002; Wing & Woodburn, 1995), the handle (e.g., Hohmuth et al., 2023), the pin (e.g., Roth et al., 1993; R. M. Smith & Loschner, 2002), or the oar blade (Elliott et al., 2002; Fuss et al., 2016).

Most of these instrumentations are ad hoc systems intended for data collection in the context of a scientific study or were used to prepare for major competitions. The installation of the sensors was time-consuming and required professional support (T. B. Smith & Hopkins, 2012). For these reasons, a professional performance analysis, such as that offered by BioRow (www.biorow.com), is hardly conceivable for regular assessments. Commercial devices aim at regular assessments, promising easy handling and precise monitoring of applied forces or power per oar. The oarlock-based Peach PowerLine devices (Peach Innovations, Cambridge, United Kingdom) is used by many rowing coaches and national rowing associations (Laschowski & Nolte, 2016). Another oarlock-based solution is the EmPower device (Nielsen-Kellerman, Boothwyn, PA, United States) whose design is based on a development by the founder of BioRow, Valery Kleshnev. In principle, these systems are very practical to control the intensity of the training or to carry out a rowing-specific performance diagnosis (Coker, 2010). However, oarlock-based instrumentations may not match the angle of the pitched bushing a rower is familiar with. In addition, oarlock-based instrumentations must cope with forces originating from the weight of the oar and forces acting parallel to the oar shaft. These parallel forces might be small when the oar is pushed outward a little bit to keep the oar in the gate. However, parallel forces can also be quite significant when athletes lean on the rigger in sweep rowing. These potential disadvantages of oarlock-based systems do not occur with instrumentation that measures bending moments directly at the oar shaft. The commercially available OarPowerMeter (Weba Sport und med. Artikel GmbH, Wien, Austria) is such an oar shaft-based instrumentation, which is mounted on the oar. The recently developed FlexOmega system (MAM GmbH, Kriens, Switzerland) also directly measures the bending moment (Mandanis & Mandanis, 2018). In the long run, the commercialisation of the FlexOmega system is targeted. Like existing products, FlexOmega allows the rowers themselves to monitor rowing strokes on water and allows detailed analysis of the recorded strokes to facilitate improving stroke/rowing technique. So far, the FlexOmega system has been validated in a static setup, but never assessed for an actual use case. Therefore, the aim of this work was to validate this new instrumentation with regard to the bending moment during a dynamic load case representing on-water rowing.

Ideally, a simultaneous measurement of the intended use case with an established measurement system is aimed at for a validation of a new measurement system. Such an established system was not available to the authors at the time of the work. It would also have been unclear which commercially available system should optimally have been chosen, as the measuring devices have so far been tested mainly statically (e.g., Laschowski & Nolte, 2016) or dynamically but unrelated to a real load case (e.g., Coker et al., 2009) or in comparison to a rowing ergometer resulting in concurrent validity (e.g., Holt et al., 2021). It was therefore decided to develop a new test bench that would allow the dynamic loading of the rowing oar based on a moment profile representing a typical rowing stroke during on-water rowing.

Next to estimating the measurement accuracy of the FlexOmega system on the newly developed test bench, this work aimed to relate the measurement accuracy found to an application of the instrumentation on the water, for example to assess the effect of a training intervention. Since we were not aware of any data on minimal meaningful differences of bending moments to which we could have referred the measurement accuracy we determined, we made the following consideration: If the overall variability during on-water rowing, given by the sum of the variability originating from the human movement execution, environmental factors and sensor characteristics, is by far larger than the measurement variability observed in the laboratory (sum of variability resulting from sensor characteristics and the test bench), it would be reasonable to argue that the accuracy of the FlexOmega system should not have a significant impact on a common performance analysis of bending moments in rowing.

Overall, this paper presents a new approach to estimating the measurement accuracy of instrumented oars in a dynamic load case to an extent not available so far. The approach was applied to a newly developed instrumented oar monitoring bending forces and the estimated measurement accuracy was related to a real-life application. Our approach contributes to a better assessment of existing or future oar instrumentation regarding their practicability for training control or performance analysis.

Materials and Methods

FlexOmega system

The FlexOmega system was developed to determine the bending moment in an oar during a stroke to subsequently derive the applied rowing power in combination with the rotational speed of the oar (Mandanis & Mandanis, 2018). An instrumented sleeve replaced a part of the shaft on the inner side of the oar next to the collar (see Figure 1). The sleeve was inserted into the shaft by first removing a shaft segment of the same length as the sleeve and then gluing the sleeve in between. The adhesive connections ensured a direct measurement of the bending moment through sensors located inside of the sleeve. Thus, the instrumentation is tied to a specific oar, which means that, for example, bending moments with different blade shapes cannot be investigated directly. Unlike other instrumentations, however, no further modification of the boat is required, minimizing setup time.

The instrumented sleeve contained sensors to measure the bending moment and rotational speed, and a data processing unit. The instrumentation was protected by Plexiglas whereby two O-rings sealed a gap between protection and sleeve so that axial sliding of the protection socket was possible which minimised any transmission of a bending moment onto the protection. To measure the bending moment, four strain gauges were tightly bound on the tension and pressure side of the sleeve, wired in a Watson Fullbridge, and continuously balanced by the null method. The attachment, temperature compensation and calibration of the strain gauges were performed by RUAG AG (Emmen, Switzerland) and DISA AG (Sarnen, Switzerland). The data processing unit, a custom-made printed circuit board (PCB) developed in collaboration with CSEM (Alpnach, Switzerland), contained a gyroscopic microelectromechanical system as well as a circuit responsible for the chronological synchronisation, amplification, and digitization of the electrical signals from the strain gauges and gyroscope.

The data processing software running on the PCB calculated physical metrics such as bending moment and rowing power from the electrical signals in real-time. Via a Bluetooth antenna, mounted on the PCB, the metrics were synchronously sent 50 times per second to an external smartphone or laptop, where the data was logged. The board was powered by a battery, which could be recharged by plugging a standard micro-USB phone charger into the waterproof socket.

On-water measurements

The on-water measurements were taken on Lake Lucerne in accordance with the Declaration of Helsinki (World Medical Association, 2013). The single scull used for the experiment was a standard racing shell that had previously been used by both participants in training and racing. It was equipped with two oars both incorporating the FlexOmega system and a smartphone (iPhone 7, Apple Inc., United States) on which the data was displayed and logged. The measurements were carried out in good and stable rowing conditions: light breeze and mild temperatures, no current. Measurements were only taken when unaffected by waves of passing motorboats.

One male rower (Rower A, aged 33, former world class athlete) and one female rower (Rower B, aged 23, national level athlete) were asked to row technically as well as possible for about 60 seconds, including distributing the applied force evenly over the drive phase, pushing first with the legs, then pulling with the back and finally with the arms, rolling back smoothly during

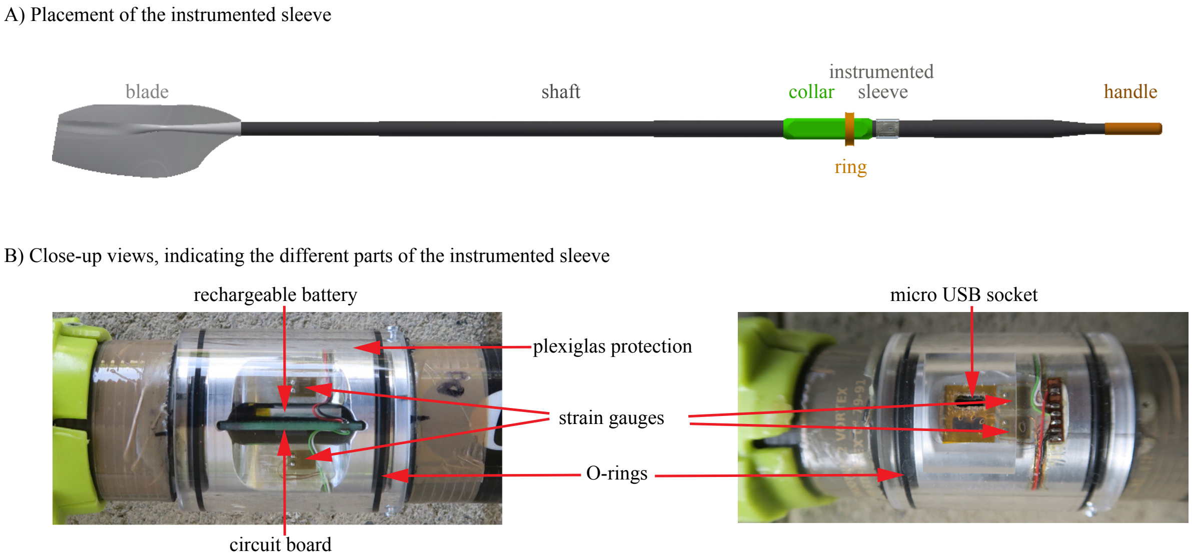

Figure 1 The FlexOmega system.

about ⅔ of the stroke time, immersing oars without splashing and not too early or too late. Rower A was requested to row at race pace whereas Rower B had to keep her stroke rate and force application at a medium level like in technique training. The two rowers and the task set for them were chosen to obtain, to a certain extent, extremes of bending moments during technically best possible rowing. On the same day, both rowers were also asked to row 13 pre-defined error patterns for about 60 seconds each. The *faulty rowing* corresponded to different combinations of deliberately ignoring aspects of technically best possible rowing. In this paper, only one error pattern will be referenced briefly in the results. After rowing each pattern, the rowers were asked to comment on their performance. The different signals were then exported from the smartphone to a CSV spreadsheet. From those, only the bending moment $M^{FO\ on-water}$ was further analysed.

For each pattern, a total of 10 to 20 strokes could be recorded. For Rower B, 13 strokes could be recorded in the technique training pattern. To be consistent, only the first 13 strokes of Rower A at race pace were considered in the subsequent data analysis.

This study focused on the validation of the sensor measurements during the drive phase. We defined this phase as the period where $M^{FO\ on-water}$ exceeded 20 Nm (Threshold was empirically derived from first on-water sessions and represented a bending moment that allowed reliable detection of the drive phase.). Processing of the data started with reviewing the video recordings to determine when relevant strokes of a requested rowing pattern began. To ensure that the boat no longer accelerated significantly on average, five strokes at the beginning of each pattern were not considered further. The remaining eight strokes were linearly upsampled (from 50 Hz to 150 Hz) to accurately find the period of the drive phase. The single drive phases were then normalised in time by linearly downsampling the data points so that each drive phase had the same number of data points $(n_{dp} = 101)$ at the end.

Test bench for dynamic loading of an oar

In order to determine the measurement variability and accuracy of the FlexOmega system independently from environmental and human influences, a test bench was developed. The test bench was constructed such that it could apply a pre-defined and known setpoint bend-

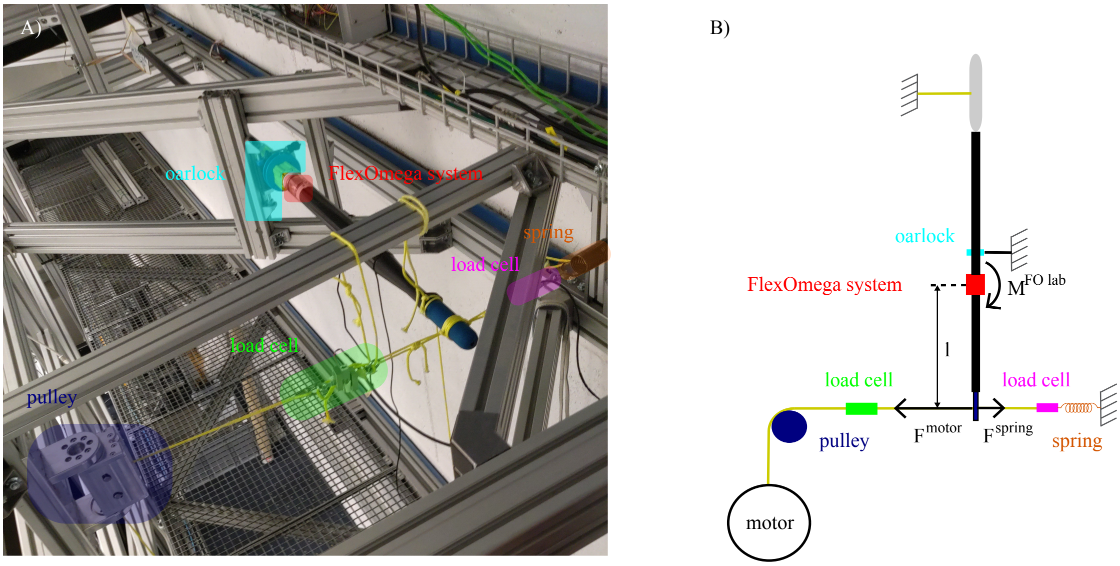

Figure 2 The test bench. (A) Entire setup except for motor which was mounted beneath. (B) Schematic of the mechanical system.

ing moment $M^{setpoint\_FO\_lab}$ around the FlexOmega system. The test bench consisted of an actual oarlock mounted to a strut profile, in which the FlexOmega oar was hinged. The oar was positioned horizontally with respect to the ground. The blade was connected with a rope to a strut profile. From one side, the grip was connected with a rope, in which a micro load cell (CZL635, Phidgets Inc., Canada) was integrated, via a pulley to a synchronous servo motor (AKM53G-ACC-NAA00, Kollmorgen GmbH, Germany). From the other side, the grip was connected in series with a rope, a helical tension-spring (19/4/1, Durovis AG, Switzerland) and another load cell (K100, Lorenz Messtechnik GmbH, Germany) to a strut profile (see Figure 2). The additional spring provided a stabilising pre-tension to the system, minimising undesired horizontal vibrations and movements when net zero force was applied to the grip. To reduce undesired vertical vibrations, the oar was vertically supported by two ropes, one attached to a strut profile and the other to the ground. Before mounting, the two load cells were calibrated using eleven known weights, ranging from 207 g to 47.5 kg.

The motor applied a predefined force profile F^{motor} to the handle. The high-level torque controller (simple proportional-integral controller) was implemented in MATLAB Simulink (Mathworks Inc., United States) and was deployed onto a target xPC (Mathworks Inc., United States) connecting to the low-level motor controller (S700, Kollmorgen SA, Germany) via EtherCat (Beckhoff Automation LLC, Germany). The force sensor output pins were connected to the xPC over EtherCat as well, allowing the conversion and processing of raw sensor data to physical force values (F^{motor} and F^{spring}) directly in the Simulink model and their logging onto the target xPC. The controller was running with a sampling frequency of 1,000 Hz at which also the data logging took place.

Test bench measurements

Two different force profiles were applied by the motor to the handle of the oar at a constant ambient temperature (24.0° C ± 2° C), each representing a stroke of either Rower A or Rower B. Profile A was based on one on-water recorded bending moment $M^{profile\ A}$ of Rower A (linearly upsampled to 1,000 Hz, resulting in 1,631 data points). Profile B was based on one on-water recorded bending moment $M^{profile\ B}$ of Rower B (also linearly upsampled to 1,000 Hz, resulting in 2,681 data points). The profiles were smoothed by a moving average filter (with a window size of 150 for Profile A and 300 for Profile B) to minimise irregularities in the profile and thus reduce the complexity of the motor controller. The setpoint force to be applied to the handle by the motor was calculated using

$$F^{setpoint\_motor} = s_{A/B}\frac{M^{profile\ A/B}}{l} \tag{1}$$

where l = 0.676 m corresponds to the length between the attachment point of the rope to the handle and the FlexOmega system (see Figure 2). The scaling factor $s_{A/B}$ was tuned to take into account the counteracting spring force, the elasticity of the oar and the rope, and control errors of the motor, such that

$$M_{max}^{setpoint\_FO\ lab} \approx M_{max}^{FO\ on-water} \tag{2}$$

for some calibration strokes recorded by the FlexOmega system in the lab or on the lake respectively ($s_A = 1.20$ for Profile A and $s_B = 1.44$ for Profile B). The setpoint for the motor torque was then fixed to

$$\begin{aligned} &\tau^{setpoint\_motor} = \\ &F^{setpoint\_motor} r = s_{A/B} M^{profile\ A/B}\frac{r}{l}, \end{aligned} \tag{3}$$

where r corresponds to the radius of the motor shaft to which the rope was radially attached.

Both profiles were repetitively applied to the oar. During the experiments, readings from the two load cells measuring F^{motor} and F^{spring} were saved onto the target xPC. Additionally, the bending moment measured by the FlexOmega system $M^{FO\ lab}$ was sent via Bluetooth to a laptop where the data was saved to a CSV spreadsheet in real-time. At the end of the measurements, data from the target xPC were imported as a MATLAB ".mat" file onto the laptop.

The resulting handle force

$$F^{handle} = F^{motor} - F^{spring} \tag{4}$$

was calculated from the sensor measurements. In addition, the setpoint bending moment at the FlexOmega system

$$M^{setpoint\_FOlab} = F^{handle} l \tag{5}$$

was determined. The target xPC had a significant memory limitation so that ultimately only a maximum of 70 consecutive strokes could be recorded for each of the two profiles A and B.

Data analysis

We assumed that the overall variability of on-water rowing $var_{on-water}$ can be expressed by a simple sum of the variability of the FlexOmega system var_{FO}, of the variability of the movement execution by the human var_{human}, and of the variability caused by environmental factors $var_{environment}$:

$$\begin{aligned} &var_{on-water} = \\ &var_{FO} + var_{human} + var_{environment}. \end{aligned} \tag{6}$$

Analogously, the measurement variability var_{lab} observed in the laboratory was formulated as follows:

$$var_{lab} = var_{FO} + var_{test\ bench}, \tag{7}$$

where $var_{test\ bench}$ corresponds to the variability of the test bench caused by modelling and control errors. We will state that if $var_{on-water} >> var_{lab}$ is found, the system error $var_{FO\ system}$ accounts for only a minor fraction of the total on-water variability. Consequently, improvements in the instrumentation would add little application-related value and detection of performance changes is mainly influenced by other measurement variabilities, i.e., how repeatable athletes row and how repeatable environmental conditions are.

For this study, we used the one standard deviation bounds to indicate the variability of measurements for a collection of strokes. The sample standard deviation was calculated for a data point at position i ($n_{dp} = 101$ for all measurements) for n_{str} strokes (either 65 for test bench trials or eight for on-water measurements) for $F^{setpoint\_motor}$, F^{motor}, $F^{setpoint\_FO\ lab}$, $M^{FO\ on-water}$ and $M^{FO\ lab}$ as

$$\hat{\sigma}_i = \sqrt{\frac{1}{n_{str}-1}\sum_{j=1}^{n_{str}}(x_{i,j}-\hat{x}_i)^{\,2}}, \quad \forall i \in \{1,\ldots,n_{dp}\}, \tag{8}$$

where

$$\hat{x}_i = \frac{1}{n_s}\sum_{j=1}^{n_s} x_{i,j} \tag{9}$$

is the sample mean for the corresponding data point (force or bending moment metrics as listed before) at position i over n_{str} strokes. The bounds were then given by

$$\hat{x}_i \ \pm\ \hat{\sigma}_i. \tag{10}$$

Additionally, we used the standard deviation as a measure of precision. We calculated the mean relative precision $\bar{p}$ as the complement of the mean relative standard deviation $\bar{r}$ over each data point:

$$\bar{p} = 1 - \bar{r}, \tag{11}$$

where $\bar{r}$ is defined as

$$\bar{r} = \frac{1}{n_{dp}}\sum_{i=1}^{n_{dp}}\frac{\hat{\sigma}_i}{\hat{x}_i}. \tag{12}$$

Also, its minimum and maximum over the stroke will be reported, i.e.

$$p_{min} = \ min\,\{1-\frac{\hat{\sigma}_i}{\hat{x}_i}\}_{i=1,\ldots,n_{dp}} \tag{13}$$

and

$$p_{max} = \ max\,\{1-\frac{\hat{\sigma}_i}{\hat{x}_i}\}_{i=1,\ldots,n_{dp}}. \tag{14}$$

Precision was calculated for F^{motor} and $M^{FO\ lab}$, with the results denoted as $\bar{p}^{motor}$and $\bar{p}^{FO\ lab}$ respectively.

To evaluate the accuracy of the test bench and the FlexOmega system, the mean of the absolute difference $\hat{d}_i$ between the forces or bending moments in question at each data point i over $n_{str} = \ 65$ strokes was calculated, i.e.

$$\hat{d}_i = \frac{1}{n_{str}}\ \sum_{j=1}^{n_{str}} d_{i,j}, \tag{15}$$

where $d_{i,j}$ corresponds either to

$$d_{i,j}^{motor} = |F_{ij}^{setpoint\_motor} - F_{ij}^{motor}| \tag{16}$$

or

$$d_{i,j}^{FO\ lab} = |M_{ij}^{setpoint\_FO\ lab} - M_{ij}^{FO\ lab}| \tag{17}$$

for all $i\ \in \{1,\ldots,n_{dp}\}$ and $j\ \in \{1,\ldots,n_{str}\}$. The average difference over the entire drive phase was defined as mean error, i.e.

$$\bar{d} = \frac{1}{n_{dp}}\ \sum_{i=1}^{n_{dp}}\hat{d}_i. \tag{18}$$

Later, we will refer to the mean relative accuracy $\bar{a}$ as

$$\bar{a} = 1 - \bar{e}, \tag{19}$$

where

$$\bar{e} = \frac{1}{n_{dp}} \sum_{i=1}^{n_{dp}} \frac{\hat{d}_i}{\hat{x}_i} \tag{20}$$

is the mean relative error over all data points ($\hat{x}_i$ corresponds here to either F^{motor} or $M^{setpoint\_FO\ lab}$). Similar to the precision, the minimal and maximal relative accuracy will also be reported, i.e.

$$a_{min} = min\ \{1 - \frac{\hat{d}_i}{\hat{x}_i}\}\ _{i=1,\ldots,n_{dp}} \tag{21}$$

and

$$a_{max} = max\ \{1 - \frac{\hat{d}_i}{\hat{x}_i}\}_{i=1,\ldots,n_{dp}}. \tag{22}$$

Analogously to (Holt et al., 2021), the mean systematic error (MSE) and the mean standard deviation ratio $(MSDR)$ was determined by

$$MSE\ = \frac{\bar{M}^{FO\ lab} - \bar{M}^{setpoint\_FO\ lab}}{\bar{M}^{setpoint\_FO\ lab}} \tag{23}$$

and

$$MSDR\ = \frac{\bar{\sigma}^{FO\ lab} - \bar{\sigma}^{setpoint\_FO\ lab}}{\bar{\sigma}^{setpoint\_FO\ lab}}, \tag{24}$$

with $\bar{M}^{FO\ lab}$ and $\bar{M}^{setpoint\_FO\ lab}$ corresponding to the mean over the strokes and data points of $M_{ij}^{FO\ lab}$ and $M_{ij}^{setpoint\_FO\ lab}$, respectively. Similarly, $\bar{\sigma}^{FO\ lab}$ and $\bar{\sigma}^{setpoint\_FO\ lab}$ corresponded to the mean over the data points of $\hat{\sigma}_i^{FO\ lab}$ and $\hat{\sigma}_i^{setpoint\_FO\ lab}$, respectively.

As an additional point, we were interested in relating the variability of the bending moment recorded on the test bench with the one recorded on the lake to see if the isolated variability of the FlexOmega system is neglectable compared to the total on-water variability that additionally includes other human and environmental factors. For this purpose, the ratio of the sample standard deviation of $M^{FO\ on-water}$ and $M^{FO\ lab}$ was computed as

$$R_i^{lab/on-water} = \frac{\hat{\sigma}_i^{FO\ lab}}{\hat{\sigma}_i^{FO\ on-water}} \forall i\ \in \{1, \ldots, n_{dp}\}. \tag{25}$$

This ratio was calculated for $n_{str} = 8$ strokes recorded on the lake and on the test bench (the first eight strokes of the 65 strokes recorded on the test bench were taken). Also, its mean over all data points was calculated, i.e.

$$\bar{R}^{lab/on-water} = \frac{1}{n_{dp}} \sum_{i=1}^{n_{dp}} R_i^{lab/on-water}. \tag{26}$$

Results

Validation of test bench

The mean error $\bar{d}^{motor}$ for the entire drive phase was 11 N for Profile A and 7 N for Profile B. In the second half of the drive phase, the control error for both profiles was about five times larger than in the first half (see Figure 3 and Figure 4).

The test bench mean relative precision $\bar{p}^{motor}$ was 99.0% for Profile A ($p_{min}^{motor} = 96.6\%$, $p_{max}^{motor} = 99.8\%$) and 98.9% for Profile B ($p_{min}^{motor} = 94.7\%, p_{max}^{motor} = 99.9\%$). The test bench's precision decreased when the loading rate of the oar was high, i.e. between about 10 to 30% of the drive phase (see Figure 4). The test bench mean relative accuracy $\bar{a}^{motor}$ was 95.2% for Profile A

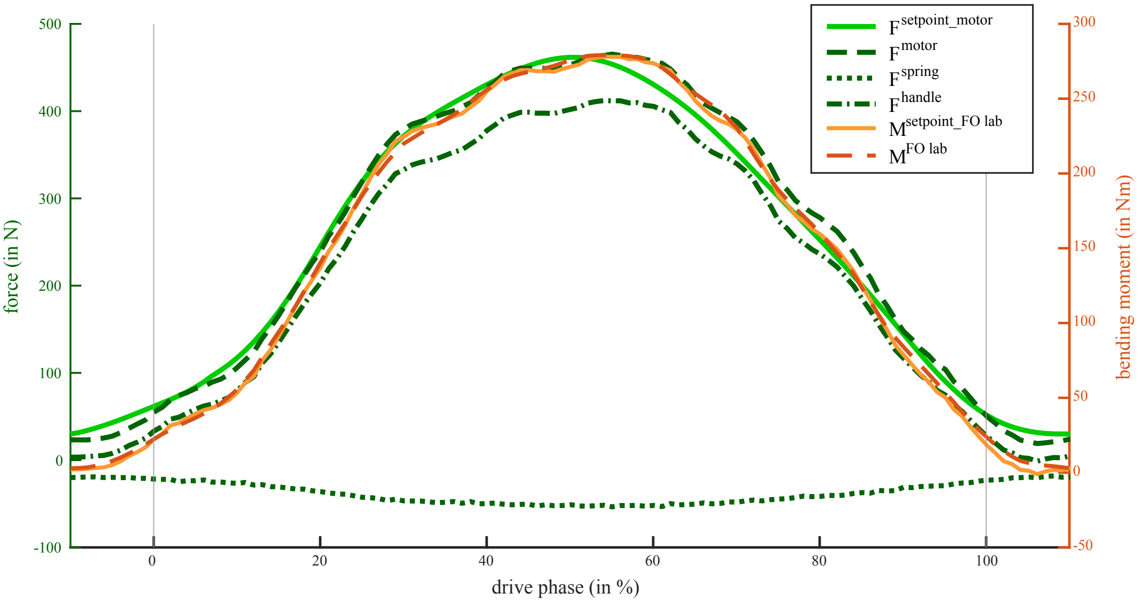

Figure 3 Examplary representation of forces and moments occurring on the test bench for Profile A. Note that the spring force F^{spring} is shown inverted to better capture the equation $F^{handle} = F^{motor} - F^{spring}$.

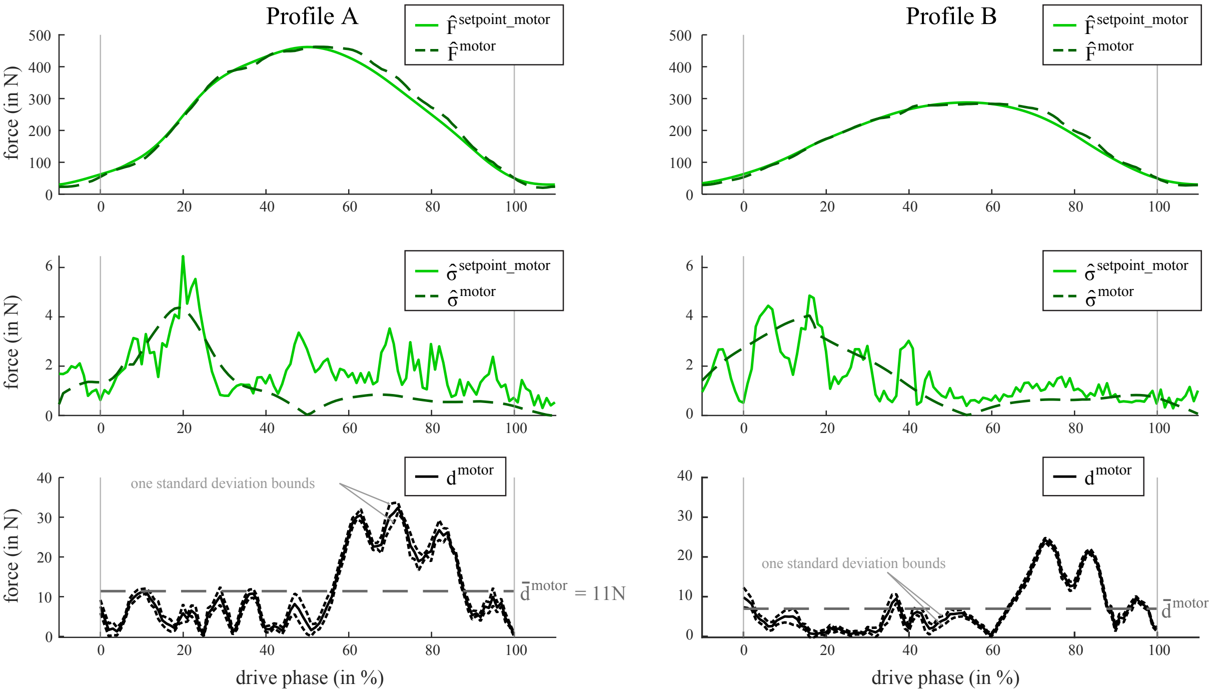

Figure 4 Mean forces applied, variability and error of the test bench for Profile A and Profile B.

$(a_{min}^{motor} = 87.6\%,\ \ a_{max}^{motor} = 99.9\%)$ and 95.6% for Profile B $(a_{min}^{motor} = 84.4\%, a_{max}^{Motor} = 99.9\%)$.

Validation of the FlexOmega system

Precision and accuracy, determined on the test bench

On the test bench, the mean relative precision of the bending moment $\bar{p}^{FO\,lab}$ was 97.5% for Profile A $(p_{min}^{FO\,lab} = 94.3\%,\ p_{max}^{FO\,lab} = 99.8\%)$ and 98.4% for Profile B $(p_{min}^{FO\,lab} = 94.9\%, p_{max}^{FO\,lab} = 99.8\%)$.

The accuracy of the FlexOmega system, given by the mean error $\bar{d}^{FO\,lab}$ for the drive phase of 65 strokes measured on the test bench was 3 Nm for Profile A and 2 Nm for Profile B (see Figure 5). The mean relative accuracy $\bar{a}^{FO\,lab}$ was 96.8% for Profile A $(a_{min}^{FO\,lab} = 80.6\%,\ a_{max}^{FO\,lab} = 99.6\%)$ and 97.3% for Profile B $(a_{min}^{FO\,lab} = 88.0\%, a_{max}^{FO\,lab} = 99.5\%)$.

The mean systematic error MSE for Profile A was 0.5% and 1.1% for Profile B and the mean standard deviation ratio $MSDR$ was 95.5% for Profile A and 10.2% for Profile B.

On-water measurement variability vs test bench variability

The mean standard deviation ratio $\bar{R}^{lab/on-water}$ was 30% for Rower/Profile A and 15% for Rower/Profile B when the technically best possible rowing was requested either at race pace (Rower A) or at technique training pace (Rower B). In faulty rowing (immersing the oar into the water too late; Rower A at 20 strokes per minute, Rower B at 22 strokes per minute), both participants rowed less consistently than in the condition in which they were requested to row as well as possible (see Figure 6); consequently, the ratio $\bar{R}^{lab/on-water}$ would be smaller.

Discussion

This study aimed to dynamically validate the FlexOmega system which has been designed to measure bending moments in an oar by an instrumented sleeve next to the collar. Because no other instrumentation was available to the authors at the time of the study that could have served as a reference during on-water rowing, a dedicated test bench was developed which allowed the application of a predefined force profile to the handle of the oar. On the test bench, the measurement variability of the FlexOmega system was determined and then related to the variability of bending moments measured during on-water rowing, to determine whether the instrumentation contributes remarkably to the measurement variability on-water.

Both rowers rowed similarly consistently on the water, the standard deviation was about 10 Nm each over long periods of the water phase. At the same time, our test bench was more variable in periods of high loading or unloading which mainly concerned Profile A. Consequently, the ratio $\bar{R}^{lab/on-water}$was markedly higher in those periods (see Figure 6). Overall, we are convinced that the on-water variability of bending moments monitored by the FlexOmega system was mainly based on variability originating from the movement execution of the athlete and environmental factors.

As a higher skill level is commonly characterised by a higher consistency of performance-relevant metrics (e.g., shown for ergometer rowing by Lay et al., 2002), we are convinced that the determined fraction of the FlexOmega system's variability to the overall variability of measured bending moments is an upper bound as the variability of the on-water bending moments almost at least doubled when the rowers were asked to make an unusual movement instead of a perfect one, i.e. when asked to intentionally enter the oar too late into the water (see Figure 6). A doubling results in halving of the ratio between the measurement variability of the FlexOmega system and the variability on water (see Equation 26 and Equation 27). Therefore, we conclude that a reduction of the measurement variability of the applied FlexOmega system would not significantly benefit users; in other words, the system is ready for rowing performance analysis.

The actual variability of the FlexOmega system is even lower than that observed in our laboratory environment as the estimation of the measurement character-

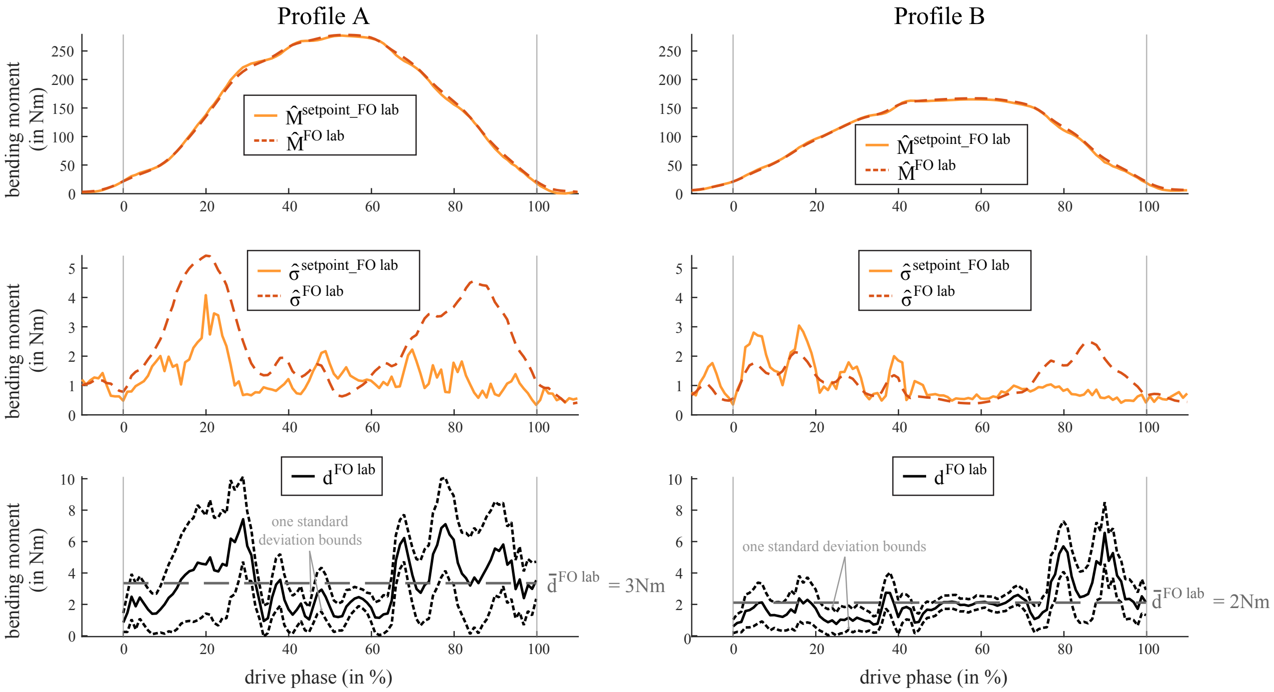

Figure 5 Setpoint bending moments and FlexOmega bending moments, their variability and difference. Details for Profile A are shown on the left, details for Profile B on the right. Top line shows mean of 65 strokes of setpoint bending moment applied on test bench in the laboratory and mean bending moments simultaneously measured with FlexOmega (FO). Middle line presents the variability of these means while lowest line presents mean and one standard deviation bounds for pairwise absolute difference between the moments.

istics of the FlexOmega system also depended on the quality of the test bench. In general, the mean relative accuracy $\bar{a}^{Motor}$ was very high (95.2% for Profile A and 95.6% for Profile B). The largest deviation from the setpoint force $F^{setpoint\_motor}$ occurred when the force was to be reduced again: Our controller lagged behind the setpoint force (see Figure 4). However, this delay of our controller did not noticeably change the characteristics of the applied force profile. In a study to determine the measurement characteristics of the rowing ergometer Concept 2, a motor was also used to simulate force profiles of athletes (Mentz et al., 2020). Characteristics of the force profile such as maximum force or power could be simulated well, only the number of strokes was 18% lower. However, the actual force profile was recorded less precisely than in our setup (cf. Figure 3 of Mentz et al.. 2020 and our Figure 4). Furthermore, the consistency of forces applied on our test bench was very high (mean relative precision $\bar{p}^{Motor}_{Profile\ A} = 99.0\%$ and $\bar{p}^{Motor}_{Profile\ B} = 98.9\%$). Consequently, our test bench was able to load the handle of the oar reliably with a force profile that represented either rowing at race pace or rowing in technique training. In the future, a rectangular or sinusoidal profile could also be used to load the oar on the test bench. In this work, however, mimicking the individual profile was the basis for comparing the variability of on-water strokes to the variability of simulated strokes.

The mean relative precision and mean relative accuracy of the FlexOmega system were very high ($\bar{p}^{FO\ lab}_{Profile\ A} = 97.5\%$, $\bar{a}^{FO\ lab}_{Profile\ A} =$ **96.8%** and $\bar{p}^{FO\ lab}_{Profile\ B} = 98.4\%$, $\bar{a}^{FO\ lab}_{Profile\ B} = 97.3\%$). When the rate of change in bending moment during the sim-

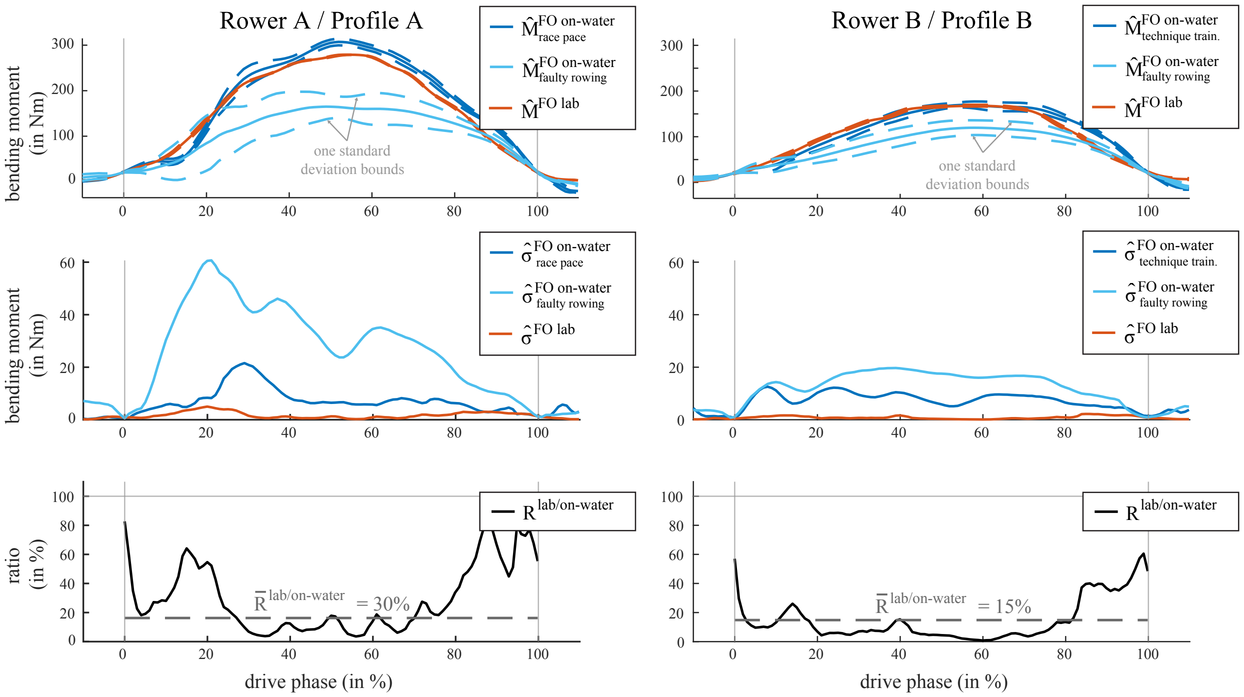

Figure 6 Comparison of measurement variability of on-water trials and trials measured on test bench. Details for Rower/Profile A are shown on the left, details for Rower/Profile B on the right. Top line shows mean and one standard deviation bounds of eight strokes recorded on-water for either rowing at race pace/technique training or faulty rowing next to eight strokes recorded on the test bench. Middle line presents one standard deviation of these means while lowest line presents ratio between standard deviation observed in the laboratory and standard deviation observed during on-water rowing at race pace/technique training.

ulated drive phase was high, the absolute difference $d^{FO\ lab}$ between the setpoint moment at the FlexOmega system $M_{ij}^{setpoint\_FO\ lab}$ and the moment measured by the FlexOmega systems $M_{ij}^{FO\ lab}$ seems to be increased (see Figure 5). This larger difference could be due to incorrect synchronisation of the data streams of the FlexOmega system and the test bench: If the data streams are inaccurately synchronised, the differences between them become noticeably larger when the rate of change of the data is high. Increasing the sampling frequency of the FlexOmega system should reduce the synchronisation error, as making the synchronisation point of 20 Nm more precise (The FlexOmega system did not allow changing the sampling frequency of 50 Hz at the time this study was conducted.). Yet, we cannot rule out the possibility that the FlexOmega system itself introduces more variability between strokes or loses some measurement accuracy at a higher rate of change in bending moment. The maximal error of around 10 Nm (see Figure 5) is below the defined threshold for the detection of the drive phase and corresponds to a deviation from the maximal measured bending moment of less than 5%. It can be assumed that for practitioners the observed differences will not affect the training program compiled from a stroke analysis made with the FlexOmega system.

In order to be able to compare the measurement quality of the FlexOmega system with other commercially available instrumentations, the mean standard deviation ratio *MSDR* and the mean systematic error *MSE* were determined. The *MSDR* for both of our profiles was in the range of the instrumentations investigated by Holt et al. (2021). If we assume that the reference system of Holt et al. (2021) measured reliably, the *MSE* calculated for both of our profiles outperformed the instrumentations by Holt et al. (2021): The lowest *MSE* was 7% (Peach PowerLine device) while we determined a *MSE* of about 1% for the FlexOmega system. However, we must note that Holt et al.'s (2021) data should be treated with caution, as instrumentations investigated by them might have been loaded beyond the intended measurement range, as the swingulator used had a much shorter outboard oar length than a common oar (Kleshnev, 2022). In addition, Holt et al. (2021) examined the rowing power while we examined the bending moment - we could not measure power with our test bench.

Principally, we expect that the FlexOmega system underestimates rowing power as deformation losses and elastic energy emitted to the water are neglected by the system. Our setpoint moment at the FlexOmega system $M^{setpoint\_FO\ lab}$ was also determined by a simple static physical model neglecting inertial terms and any deflection of the oar due to bending. Another inaccuracy of the test bench resulted from the handle displacement which was about 0.2 m for the maximal force of Profile A decreasing the right angle between the rope and the oar by roughly 17°. Consequently, the bending moment was theoretically reduced by about 5% in the worst case, as estimated from

$$F^{perp} = cos(17^{\circ})F^{motor} = 0.956 \cdot F^{motor}, \tag{27}$$

with F^{perp} corresponding to the actual force acting perpendicular to the oar. Furthermore, the vertical ropes attached, which should reduce vertical vibrations during the tests, created an additional, counteracting spring force that further minimised F^{perp} at larger bending deflections. In the future, empirical correction factors could further improve the validity of the test bench, whereby we consider the current test bench version to be quite suitable for dynamic evaluations of an oar sensor.

Another limitation of the test bench was that the target xPC used did not have enough memory to record an endurance test of around 250 strokes corresponding to a 2,000 m rowing race. As neither the accuracy nor the precision of the FlexOmega sensor decreased during the 65 strokes analysed, we decided against upgrading the test bench to be able to record more than 65 strokes as no further insights were expected. We have also not tested how temperature affects the measurement properties of the FlexOmega system. Theoretically, the arrangement and wiring of the embedded strain gauges should compensate for temperature fluctuations. However, temperature fluctuations of 30° C can certainly occur, for example when an oar is taken out of the wheelhouse and then used in the blazing sun. Thus, a future validation of the FlexOmega system should elaborate the impact of temperature.

Conclusion

With a newly developed test bench, an oar was repeatedly dynamically loaded by a force profile representing the drive phase during on-water rowing. Since the force profile was applied at the handle of the oar with high precision and accuracy (on average 99% and 95% respectively), and the oar was hinged in a typical oarlock, in principle any instrumented oar or oarlock could be evaluated with our test bench.

For the FlexOmega system, a mean error in the bending moment of 3 Nm and a mean accuracy of 97% was determined on the test bench for the force profile representing a former world class athlete rowing at racing speed. If we take also into account that the measurement variability observed on the test bench was about 30% of the measurement variability that occurred during on-water rowing (and by far less in case of a younger athlete or in case of faulty rowing), we conclude that an improvement of the measurement characteristics of the FlexOmega system does not promise any practical benefit and that the system in its current version can be used to control training intensity, track training load or to assess rowing performance.

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Competing interests

Georges Mandanis is the inventor of the FlexOmega system used in this study. Timon Wernas and Michael J. Schmid supported the development of the FlexOmega system as external advisors. The other authors have declared that no competing interests exist.

Data availability statement

Data acquired and analysed during the study are available from the corresponding author on reasonable request.