SonicSeat: A Seat Position Tracker based on Ultrasonic Sound Measurements for Rowing Technique Analysis

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ABSTRACT
A significant share of rowers does not have access to professional supervision by coaches. However, proper technique is a key component for both success in competitions and to prevent injuries or long-term induced postural deformity. In cooperation with national rowing coaches we developed a sensor system to continuously monitor the rower's seat position. It allows offline data analysis and complements existing state-of-the art methods to analyze rowing technique based on video footage. Both quantitative analyses for coaches as well as qualitative and visual feedback for athletes are provided. We tested our system on the water and present exemplary data and analyses.

Categories and Subject Descriptors
J.2 [**Physical Sciences and Engineering**]: Electronics, Engineering

General Terms
Algorithms, Measurement, Experimentation

Keywords
Rowing, Sliding Seat, Ultrasonic sound, Position monitoring

1. INTRODUCTION
Rowing is one of the oldest Olympic disciplines and is very popular for both spectators and athletes. The rowing population is growing by 5% annually in the United States [4]. Besides junior, high school, collegiate or elite athletes who are usually member of a well-structured and supervised rowing program, the population of adult rowers almost doubled between 2004 and 2008 [4] and is usually less organized and not supervised by coaches. Nevertheless, rowing technique comprises a complex motion sequence and proper exercise is not only essential to win races but also to prevent injuries [6]. There is a broad knowledge about the ideal rowing techniques [6, 9]. To teach technical skills, coaches mostly rely on their eyes and simple technical tools like video cameras [11]. However, coaches are not available all the time and there is a need to support rowers with automatic tools to enable self-assessment even when no coach is available [8].

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1.1 Rowing Technique
Rowing is a sequence of strokes with the goal to move the boat forward as fast as possible. One stroke of the basic rowing technique is illustrated in Figure 1. From the finish position (1) the rower stretches his arms and leans his upper body forward. Subsequently, the rower moves his sliding seat to the stern by bending his legs. This recovery phase (2) ends with the catch (3) where the blades are placed in the water. During the drive phase (4) the rower moves the boat forward by pulling the oars. This is achieved by extending the legs (4) and then pulling with the upper body and arms (5). In the finish position (6) the rower levers the oar blades out of the water and feathers them parallel to the water's surface. This should happen in the angular point between forward and backward movement.

Figure 1: One cycle of rowing [3]: From the finish position (1) the seat slides forward during the recovery phase (2). In the catch position (3) the blade dips into the water. During the drive phase (4), the blade is pulled through the water and the sliding seat moves towards the bow (5). At the finish position the blade goes out of the water (6) and a new cycle starts.

The sliding seat allows the rower to use his legs to achieve a longer and more powerful stroke compared to a fixed seat. The legs are the most powerful limbs involved in rowing, 70% of the total expended energy is contributed by the legs. At the same time, the sliding seat movement is also one of the most sensitive part in rowing technique. The sliding of the seat goes in line with the movement of the rower’s body. The weight of the rower is typically at least five times higher than the boat’s weight. Thus, the sliding seat movement is directly linked to the movement of the center of gravity. A proper technique for moving the sliding seat is essential to avoid unintended vertical or rotational movements of the boat. This stabilizes the boat, minimizes the loss of speed and minimizes the risk of injury. Thus, the right coordination of the legs is for both beginners and advanced rowers an essential and challenging part when improving their rowing technique.

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1.2 Previous Work

In previous work we proposed a boat area network, which consists of multiple inertial measurement units, which are attached to the boat and the oar [14, 10, 11]. Based on the measured data, the orientations and movements of the boat and the oar were analyzed. With this system, coaches and rowers are able to benchmark their oar movement patterns to the ones of other rowers in an objective, quantitative way. However, the movement of the oar is the result of the coupled and coordinated actions of multiple sub-movements of many limbs. Knowing the resulting oar movement, it is still hard to derive causes for deviations and propose appropriate suggestions on how to improve the technique. The two sub-movements known to influence most the oar movement are the swing of the rower's upper body and the sliding of the seat [9].

In this work we extend our existing boat area network with an additional sensor node to track the position of the sliding seat. We explore the technical feasibility and potential of such a new subsystem.

1.3 Related Work

The most spread system to monitor the sliding seat movement is the StrokeCoach device by NielsenKellermann [1]. It is a commercial device to count the seat movements with a magnet and a reed switch. The goal of the system is to calculate and display the current stroke rate. There is no possibility to derive the seat position.

Kleshnev [12] and Smith [13] present a method to measure the seat position based on a cord which is connected to a potentiometer. The cord is attached to the sliding seat. Measurements can be done in an easy and stable way. However, the system interferes directly with the rower, the attached cord constantly pulls the seat backward.

Davoodi published a system to track the seat position by optical methods [7]. This system works well for indoor rowing. However, this approach is not yet tested for on-water environments.

1.4 Contributions

With this work we aim to advance the state of the art in the following aspects:

- We describe the design and implementation of a contactless measurement system for monitoring the sliding seat's movements in on-water environments. We demonstrate the technical feasibility in a proof-of-concept study.
- We introduce quantitative performance metrics to rate rowing technique based on sliding seat movements.
- We provide a fully automated rowing data analysis tool to calculate and visualize these metrics.
- We extend the currently most common approach to analyze rowing technique, inspection of video footage, by two additional functionalities: the automatic segmentation of strokes and the inclusion of subtitles.

2. SEAT POSITION TRACKING SYSTEM

2.1 Requirements

In discussions with professional rowing coaches and athletes of different skill levels we identified the following requirements for an ideal seat position tracking system:

Continuous measurements. The system should be able to record continuous data of a whole training session, which usually lasts between one and two hours. The system must be easy to use, e.g., not requiring the user to change batteries or storage volumes during exercise.

Unobtrusiveness. The rower should as little as possible be distracted or influenced by the system. This implicates a small form factor and weight of the system and contactless measurement methods.

Accuracy. The system's accuracy should be at least comparable to the perception skills of an experienced coach.

Rules. To allow the usage of the system also in competitions, the appropriate racing rules have to be respected. All international rowing competitions and most of the national rowing federations implement the FISA[1] rules of racing [2], which prohibit any devices that enable communication with outside the boat. Therefore, the system either has to feature live feedback capabilities for the rower or record the data for later offline analysis.

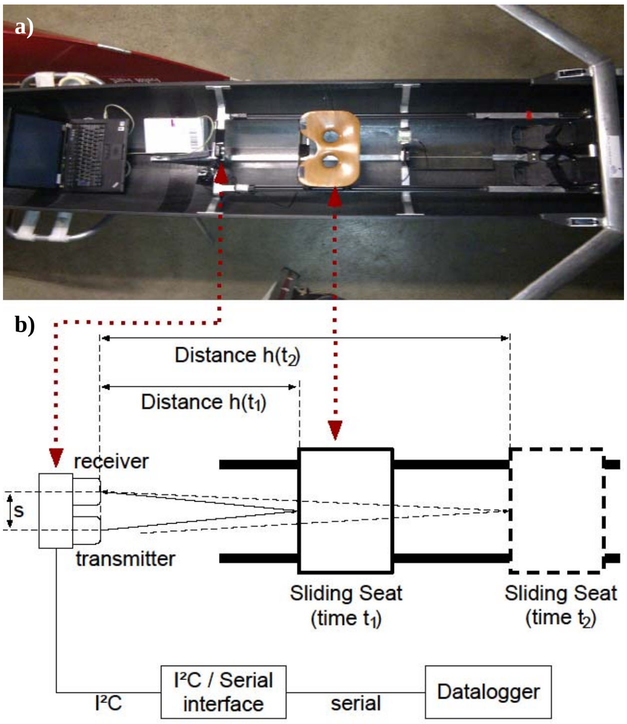

Figure 2: Ultrasonic sound based sliding seat position tracker (b) mounted in a rowing boat (a). It consists of an ultrasonic sound transmitter and receiver unit which is attached to the boat shell and points to the sliding seat.

[1] The Fédération Internationale des Sociétés d'Aviron (FISA) is the international rowing federation.

2.2 Seat Tracking based on Ultrasonic Sound

We propose a contactless seat tracking system based on ultrasonic sound distance measurement. In a pre-study we optimized the system configuration and the mounting to the boat. In the following we describe the final setup. We opted for the Devantech SRF08 Ultrasonic Range Finder. It represents a low-cost (<$50) module comprising an ultrasonic sound transceiver. Technical specifications are listed in Table 1.

Table 1: Specifications Ultrasonic Range Finder [5]

Parameter	Value
Manufacturer	Devantech Ltd.
Model	SRF08
Size	$43x20x17\ mm^3$
Size incl. housing	$55x34x30\ mm^3$
Weight incl. housing	$19\ g$
Current Consumption (ranging)	$12\ mA$
Current Consumption (standby)	$3\ mA$
Voltage	$5\ V$
Measuring steps	$4\ \mu s$ (equals $\sim 0.9mm$)
Connection	I²C Bus
Accuracy	$4\ cm$

The module is aligned to the boat with the ultrasonic beam pointing towards the sliding seat as depicted in Figure 2. It turned out during the pre-study that the position behind the seat is in favor compared to the front position: This way, the module does not interfere with the rower's legs and the system disappears from the rower's sight. The module sends out sound bursts at a frequency of $40\ kHz$ and measures the time interval until the echo is received. With the measured sound travel time t_i, the sound velocity in air c_{Air} and the distance s between transmitter and receiver, the position h of the sliding seat can be obtained according to equation (1).

$$h(t_i) = \sqrt{\left(\frac{c_{Air}(T)\cdot t_i}{2}\right)^2 - \left(\frac{s}{2}\right)^2} \qquad (1)$$

The sound velocity in air c_{Air} depends on the current air temperature T:

$$c_{Air}(T) = 331.5\frac{m}{s}\sqrt{1 + \frac{T/°C}{273.15}} \qquad (2)$$

In our pre-study we measured a maximum temperature variation during one training session of $4\ K$ ($15°C$ to $19°C$). For the sake of simplicity, we calculate the average temperature and assume this to be the constant temperature during one measurement session. This simplification introduces a maximum error of less than 1%. Thus, the error range of the ultrasonic module of up to $4\ cm$ is still dominating.

The sensor module is connected through its I²C bus interface to a data logger to save the data to a SD card. The maximum sampling frequency is limited by the maximum travel time t_{max}, which the sound needs for the maximum expected seat distance h_{max}:

$$f_{max} = \frac{1}{t_{max}} = \frac{c_{Air}(T)}{2}\left(h_{max}{}^2 + \left(\frac{s}{2}\right)^2\right)^{-0.5} \qquad (3)$$

The upper limit for our setup calculates to $f_{max} \approx 160\ Hz$. We chose a sampling frequency of $f_s = 100\ Hz$, which we found to be sufficient for our application.

3. TRAINING ANALYSIS

3.1 Performance Metrics

As outlined in section 1.1 the proper movement of the sliding seat is a key component for a good rowing technique. Coaches and rowing literature offer a broad variety of advices how an ideal seat movement should look like. In this work we focus on the most important features as described by leading rowing associations [2, 6, 9]. Based on the qualitative descriptions in literature and in collaboration with national rowing coaches of Germany and Switzerland we propose measures which represent the rower's performance quantitatively.

The described measures are visualized in Figure 3.

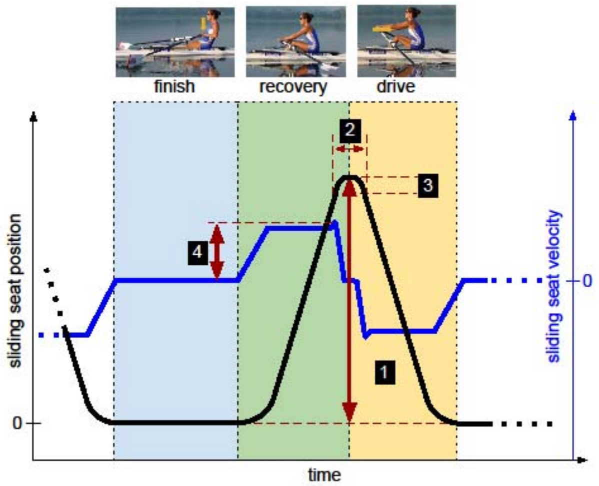

Figure 3: Sliding seat movement (black line) and seat velocity (blue line) during one rowing cycle. Extracted performance metrics are the total seat displacement Δh_n (1), the maximum sliding velocity $v_{max,n}$ (4) and the catch delay $= \Delta t_{delay,n}$ (2). Label (3) depicts the tolerance interval Δh_{tol} during which deviations of the catch position are still counted as pause. (Pictures have been taken from [3].)

3.1.1 Stroke Rate

The seat movement is segmented into N separate strokes by detecting the local minimums that represent the finish positions.

$$h(T_n) = h_{min,n}\ ,\ \ n = 1..N \qquad (4)$$

The stroke rate $f_{rate,n}$ is the reciprocal time interval between two strokes. It is measured in strokes per minute:

$$f_{rate,n} = (T_{n+1} - T_n)^{-1}\ ,\ \ n = 1..(N-1) \qquad (5)$$

3.1.2 Catch Delay

In the catch position the center of gravity is located at the stern of the boat. The longer the pause at this position is, the more the boat's stern rotates into the water and decelerates the boat. Therefore, the blade should go into the water and start the next stroke as soon as the most forward position, the catch position, is reached. The catch position is represented by the local maximum of the $h(t_i)$ curve:

$$h(t_{catch,n}) = h_{max,n} = \max_{t_i \in (T_n; T_{n+1})}(h(t_i)) \quad (6)$$

We define the catch delay $\Delta t_{delay,n}$ as the length of the time interval during which the seat position resides within the range of $\pm\Delta h_{tol} = 4\ cm$. The range is chosen according to the expected measurement accuracy of the ultrasonic measurement module.
Finally, we compensate for variations of the current stroke rate $f_{rate,n}$ and normalize the catch delay to a stroke rate of $f_{norm} = 20/min$:

$$\Delta t_{delay,norm,n} = \Delta t_{delay,n} \cdot \frac{f_{norm}}{f_{rate,n}} \quad (7)$$

3.1.3 Maximum Sliding Velocity

The sliding seat should move in a uniform smooth motion. Sharp acceleration and velocity peaks cause unintended boat movements and vibrations and should be avoided.
We derive the seat velocity $v(t_i)$ as the difference between two successive discrete seat positions:

$$v(t_i) = f_s \cdot (h(t_{i+1}) - h(t_i)) \quad (8)$$

The maximum seat velocity is calculated as the highest peak within the time interval of one stroke:

$$v_{max,n} = \max_{t_i \in (T_n; T_{n+1})}(v(t_i)) \quad (9)$$

Again, this measure is normalized to stroke rate f_{norm}:

$$v_{max,norm,n} = v_{max,n} \cdot \frac{f_{norm}}{f_{rate,n}} \quad (10)$$

3.1.4 Sliding Seat Displacement

The rower should stick to a long stroke length, even with high stroke rates like during racing conditions [9]. Besides the arm and upper body movement, the sliding seat displacement Δh_n is the main contributor to achieve a long stroke length:

$$\Delta h_n = h_{max,n} - h_{min,n} \quad (11)$$

3.2 Data Analysis

3.2.1 Sliding Seat Data

After exercise, the data is transferred to a computer and then processed by our rowing data analysis tool. The tool is fully automated and does not require any user input. It performs the stroke segmentation and calculates the performance metrics for all strokes as described above. Additionally, for the catch delay values a binary classification is performed to identify which strokes are significant worse than average. The threshold value τ_{delay} for this classification is chosen as the sum of the median value and the standard deviation:

$$\tau_{delay} = median(\Delta t_{delay,norm,n}) + std(\Delta t_{delay,norm,n}) \quad (12)$$

Thus, the threshold value is different for each rower and each practice. It allows a quick identification of the strokes of a practice, which potentially require most awareness. A similar classification was performed for the maximum normalized sliding velocity values $v_{max,norm,n}$.
The resulting values can be inspected as a plain time series for custom computations, and they can also be visualized for every single stroke.

Figure 4: Video footage is automatically segmented into separate strokes and the stroke numbers are displayed as subtitles.

3.2.2 Video Footage

Our rowing data analysis tool offers the possibility to import video footage which was recorded during the practice. After synchronizing the video with the seat data, the video data is automatically segmented by strokes and annotated. This allows the rower or coach to replay specific stroke numbers or to watch multiple strokes with continuously updated performance evaluations displayed as subtitles within the video. An example is shown in Figure 4.

4. APPLICATION ON THE WATER

In this section we present exemplary data from a rower who used the system during exercise on the water. To ensure diverse data, the rower was accompanied in a motorboat by a coach who prompted him to perform several technical drills which provoked either a good or a bad technique. In total, the data set consists of 223 complete strokes. Additionally, the training session was recorded with a video camcorder. After the practice we used our rowing data analysis tool to examine the rower's exercise. Exemplary results of two single strokes are shown and explained in Figure 5 and Figure 6. The first one shows a short stroke, which is considered average in respect to catch delay and seat velocity. The second stroke shows a longer catch delay and a significant peak in the sliding velocity. This bad technique is called "rushing the slide" and is a typical mistake done by rowers at beginner level [9].

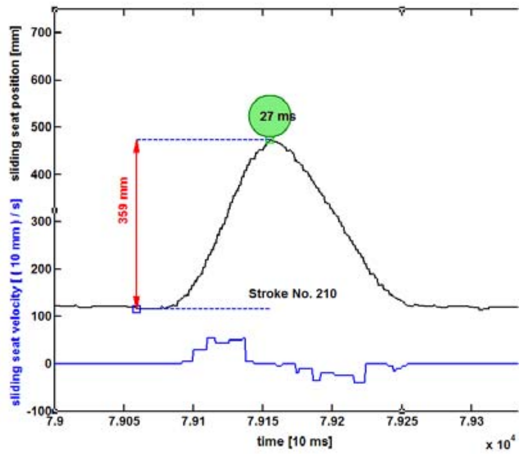

Figure 5: Stroke number 210: The measured sliding seat displacement is 359 mm. The delay at catch position is 27 ms. This value is marked with a green bubble, which highlights that this value is not considerable bad in comparison to the average stroke within the session.

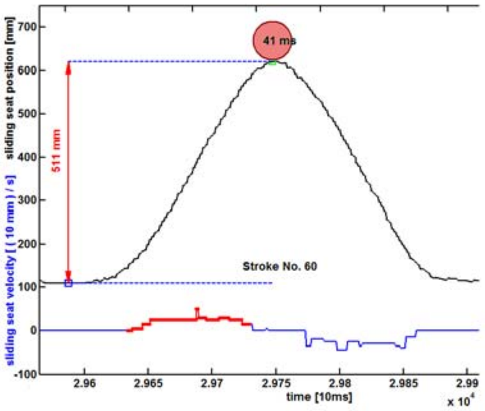

Figure 6: Stroke number 60: In this example, the stroke length is 511 mm. The delay at catch position is 41 ms, which is considered an already pathologic value and therefore is marked by a red bubble. Additionally, the peak in the velocity curve (bottom) is also significantly worse (red line) in comparison to the other strokes of the same session.

We asked two experienced elite level (world cup) rowers to decide solely based on the recorded video footage which strokes they rate as "significant *worse* than average" for the given dataset in respect to (A) catch delay and (B) unsmooth sliding motion. The remaining strokes were rated as "*average*". In a first run, the experts drew their decisions individually. Then, they discussed the strokes where their individual rating differed until they agreed upon a common rating. We considered the expert's rating as golden standard and compared it to the classifier's result. The strokes which were recognized as *worse* by both the golden standard and the classifier were counted as true positives. The strokes which were rated as *average* by both the golden standard and the classifier were counted as true negatives.

In case the classifier disagreed with the golden standard the stroke was treated as false positive (experts rated *average* and classifier rated *worse*) or false negative (experts rated *worse* and classifier rated *average*). Based on these stroke counts, the specificity values and sensitivity values are calculated according to the following equations:

$$Specificity = \frac{True\ Negatives}{True\ Negatives + False\ Positives} \quad (13)$$

$$Sensitivity = \frac{True\ Positives}{True\ Positives + False\ Negatives} \quad (14)$$

In respect to catch delay (maximum normalized sliding velocity) the classifier achieved a specificity of 90% (98%) and a sensitivity of 100% (100%). An excerpt of the classification result in respect to catch delay for ~50 strokes is depicted in Figure 7.

To induce different stroke lengths, the rower was instructed to perform a 400 m test race. The recorded data is shown in Figure 8. The data represents a typical race profile. This includes a start phase with short and high strokes, then a steady-state rowing phase with constant length and rate, and the final sprint with increasing stroke rates and decreasing seat movement.

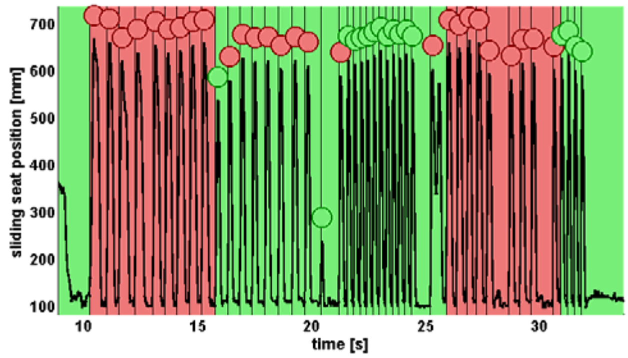

Figure 7: Comparison of automated classifier with expert's rating. Red background color means that experts rated the catch delay of the stroke as "worse than average". Red circles represent the analog rating as result of the automated classifier.

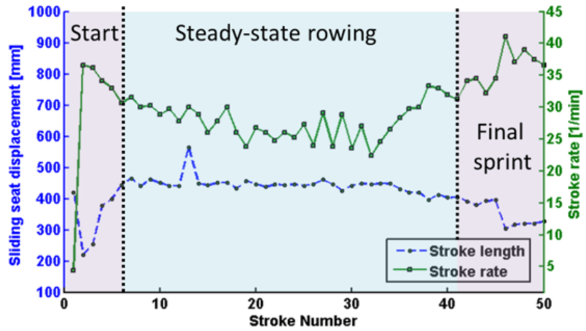

Figure 8: Sliding seat displacements and stroke rates during a 400 m test race.

4.1 Limitations

Although, we tried to meet most of the requirements mentioned in section 2.1, we are aware that this work is only one step towards the envisioned ideal system and it still involves some limitations.

Limited parameters. Our approach only takes into account the sliding seat movement. Although, this aspect is of great interest for the rowing community, there are additional parameters of interest that are not yet covered by our system. We are in the progress to extend the system accordingly.

Single-User study. The goal of this work is to motivate and describe the implementation of a new sensor modality for rowing technique monitoring systems. To believe in a potential value of the system we rely on literature and feedback from experts. Although we conducted a user study, we cannot prove any statistical relevance due to too small user numbers. This work is a first step, which shows the technical feasibility and will be the foundation for a more significant user study to follow.

Unobtrusiveness. An ideal measurement system does not interfere with the measured object. Although we restricted the additional volume and weight, which was mounted to the boat to a minimum, the adjustments could be influencing the rower knowingly or unknowingly.

5. CONCLUSION AND OUTLOOK

We presented a newly developed contactless seat position tracker for rowing boats based on ultrasonic sound measurements. We described the system design and presented exemplary data from a first on-water measurement.
In collaboration with rowing experts we identified performance metrics to rate rowing technique based on sliding seat movements and introduced quantitative representations. We presented a rowing data analysis tool, which calculates and visualizes these performance metrics. Additionally, it complements the state-of-the art method for analyzing rowing technique by video footage with two additional functionalities: the automatic segmentation of strokes and the inclusion of subtitles.

In a next step we will integrate this new sensor modality into our existing boat area network [14, 10, 11]. For the application in rowing trainings we will include real-time feedback to the rower and to the coaches. The sensor network will be extended to rowing boats with more than one rower to analyze and improve crew synchrony.

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