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MONITORING AND EVALUATION OF ROWING PERFORMANCE USING MOBILE MAPPING DATA

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ABSTRACT: Traditionally, the term mobile mapping refers to a means of collecting geospatial data using mapping sensors that are mounted on a mobile platform. Historically, this process was mainly driven by the need for highway infrastructure mapping and transportation corridor inventories. However, the recent advances in mapping sensor and telecommunication technologies create the opportunity that, completely new, emergent application areas of mobile mapping to evolve rapidly. This article examines the potential of mobile mapping technology (MMT) in sports science and in particular in competitive rowing. Notably, in this study the concept definition of mobile mapping somehow differs from the traditional one in a way that, the end result is not relevant to the geospatial information acquired as the moving platform travels in space. In contrast, the interest is placed on the moving platform (rowing boat) itself and on the various subsystems which are also in continuous motion.

As an initial step of an on-going research this article discusses the biomechanics of rowing in relation to applied technique and equipment. Also, it reviews the current practices and sensor systems used for monitoring and evaluating performance in rowing. Finally, it presents an integrated data acquisition and processing scheme for rowing based on modern MMT. To this effect, a critical assessment of the various types of sensors as well as their installation and integration into a recording system is detailed. This analysis benefits by a number of preliminary tests using real data recordings. The boat kinematics (velocity, acceleration and attitude), techniques for their noise elimination and processes for computing average stroke characteristics are studied thoroughly. Also, the pattern of motion in rowing (stroke cycle) is examined in relation to athlete technique and capacity.

1. INTRODUCTION

As in most endurance sports, the primary goal in competitive rowing is to achieve the maximum mean velocity for the duration of the race. This task requires a highly efficient rowing stroke that represents the outcome of three distinct but dynamically interacting factors – namely, the athlete, the rowing equipment and the environment. In the past, various systems have been developed to record the boat kinematics using positioning and attitude sensors. Most of these studies aim at a qualitative analysis and interpretation of the phases of the rowing cycle whereas, a lesser attention was paid on positional accuracy, sensor synchronization and data integration. Also, various models have been presented that aim to analyze boat kinematics in relation to applied technique. Such models reside on the physical laws underlying the rowing scenario and on measurements taken on the athletes' body and equipment. Nevertheless, given the complex character and the dynamic interrelations of the factors that affect a rowing race, today there exists a very limited number of studies in the literature that attempt a holistic approach to the problem.

We argue that the use of MMT can contribute effectively to the study of the rowing problem in a rigorous and integrated manner. Multiple mapping sensors if combined effectively with other type of sensors placed on the boat, the oars and the athlete can provide base information allowing for fine recording of the entire system in motion. The high positional accuracy, the increased sampling rates, the possibilities for improved time stamping among sensors, in common with the recent advances in wireless telecommunication technology and collaborative mapping can further contribute to the development of a feedback system to provide the athlete with reliable, quantitative information about the rowing mechanics. This paper is divided in two parts. In the first part we discuss the basics in rowing biomechanics and attempt a review of existing systems in monitoring rowing performance. In the second part we focus on the design requirements that imply the development of an integrated recording and evaluation system. This analysis is based on the literature as well as on the evaluation of a subset of real mobile mapping data captured using a prototype system developed by the authors, featuring a high frequency GNSS and a MEMS-IMU unit.

2. BIOMECHANICS OF ROWING AND TECHNOLOGY

2.1 The Rowing System and Technique

In rowing, three factors primarily affect the final race time; the athlete, the rowing equipment (boat, oars, seat, etc.) and environmental parameters (wind speed, currents, etc.). From these key factors, the most influential but also the most complex and hard to determine is the rower. In fact, the moving power of a rowing boat depends on the capacity (physical strength or fitness) of the athlete and the athlete's level of proficiency (technique). Rowing technique has a great influence on the stroke rate and distance traveled during the stroke cycle. This affects the average boat velocity which by extension determines the success of a race.

As shown in Figure 1, rowing is a periodic movement. The catch involves placing the oar blade in the water. Then in order to move the boat the rower drives the oars against the foot stretchers to pull the blade through the water. The finish is defined by the removal of the blade out of the water. During the recovery the rower moves slowly back up the slide towards the catch and feathers the oar blade so is perpendicular to the surface of the water ready for the next drive. Clearly, in order to achieve a good rowing performance an efficient but consistent stroke-to-stroke paddling is deemed necessary. Obviously, if two or more rowers are onboard the same vessel then, the influence of crew movement patterns on boat velocity fluctuations is maximized and therefore, this goal becomes even more challenging. Therefore, it becomes evident that detailed and accurate feedback information about the kinematics and forces acting on the boat would play an important role in performance optimization.

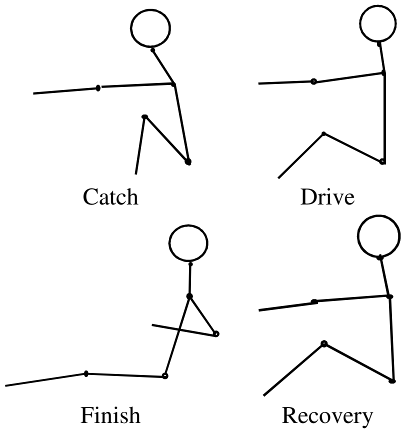

Fig. 1. The phases of stroke cycle in rowing

2.2 Rowing Kinematics, Kinetics and Environmental Parameters

Rowing biomechanics deal with the precise measurement of forces and kinematics of the rowing system (i.e., the athlete, the boat and oars). Also, it develops theoretical models to explain and optimize the complex interactions between athletes and equipment. As a result, the outcome of biomechanical studies is applied to the practical task of improving boat velocity.

Biomechanical parameters can be classified in categories of their source of origin. In this approach the kinematics, the forces and environmental factors acting on the rowing system can be classified in four categories; namely, the athlete, the boat, the rowing equipment and the environment (see Figure 2). Another way to classify and study the biomechanical parameters is in terms of their mechanical area – namely, the kinematics, kinetics and external parameters. Rowing kinematics includes boat kinematics (velocity, acceleration, attitude), oar angles, seat and trunk displacement as well as attitude of the athlete body (position of knees, elbows, back). On the other hand, rowing kinetics deal with the forces applied by the rower (handle, foot stretcher), the blade forces and the vertical seat force developed during the stroke cycle. Other forces and momentums (hydrodynamic, gravitational) can also be taken into account. Finally, environmental parameters include external influences (wind direction and velocity, water temperature and currents) acting on the rowing system.

During a race, this multitude of biomechanical parameters evolves rapidly and their components are in continuous interaction each other. Also, other factors (e.g. physiology, psychology, sports medicine) that affect energy production and efficiency of the athlete, interrelate directly with biomechanical parameters and by extension to performance. According to the above analysis the rowing problem is a challenging task; and therefore, its study requires both the design and implementation of fine measurement and sophisticated analysis systems.

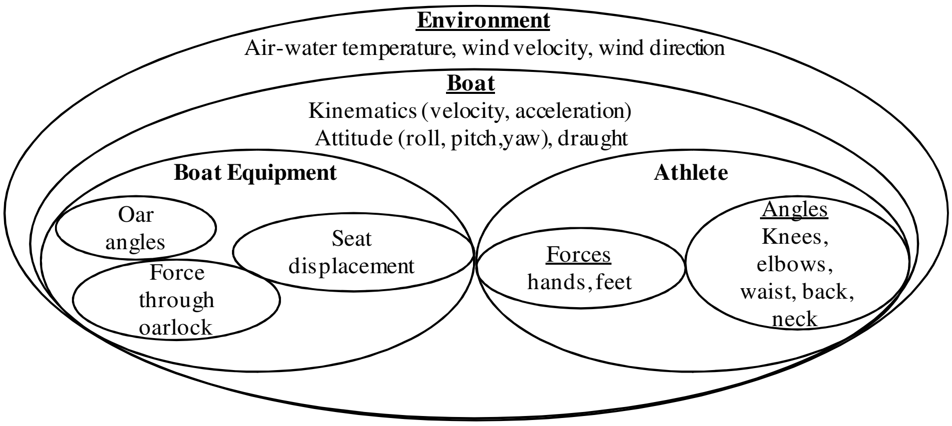

Fig. 2. A classification of biomechanical parameters in rowing in terms of their source of origin

2.3 Classification of Performance Monitoring Systems in Rowing

Performance monitoring in rowing dates back to early 20th century. Since then a great number of researchers reported on the factors influencing rowing performance ranging from biomechanics to physiology, psychology and sports medicine. As a general remark, most studies and systems concerned with the recording of rowing biomechanics provide only some basic measurement information and simple statistical analysis tools to assist the coach and athletes during training. However, there is a number of studies that propose specific modelling approaches and their validation results using either simulated, ergometric or on-water rowing data. Depending on motivation and specific goals, these studies concentrate either on the influence that crew movement patterns imply on boat velocity fluctuations [Smith & Spinks, 1995; Elliott *et al.*, 1993], the development of feedback systems to improve rowing training [e.g. Hawkins, 1999; Smith and Loschner, 2002] or even on equipment design optimization [Caplan and Gardner, 2007].

Nevertheless, as a matter of fact, the ultimate goal of these studies is concerned with the prediction of boat velocity and the definition of indices suitable for evaluating rowing performance. Obviously, the underlying theoretical hypotheses, the modelling approach and level of complexity differs from study to study. For instance, the models proposed by Millward, 1987; Lazauskas, 1997 and Simeoni *et al* 2002 are simpler compared to those presented by Van Holst, 2004, Atkinson, 2004 and Cabrera *et al*, 2006. For example, and as opposed with previous models, Van Holst, (2004) considers drag and lift forces on the blade and, Atkinson, (2004) assumes flexibility conditions on the oar.

With the exemption of theoretical studies that rely purely on mathematical pre-analysis tools, biomechanical modelling resides on measurement feedback. A number of data acquisition systems are currently available featuring different design characteristics. For instance, Zhang, (2008) proposes a real time athlete tracking system which integrates low-cost GPS, MEMS-IMU, magnetometers and wireless communication. This system measures the athlete trunk position; however, is not suited to monitor boat kinematics, neither oar kinetics. Bettinelli *et al* (2010) describe an on-water system suitable for monitoring rowing performance. This system offers a fairly integrated monitoring solution; however, it does not measure vertical oar angle and athlete's joints angles. Finally, Llossa *et al* (2010) present a wireless network system, the measurement principle of which relies on a number of three-axial MEMS units – nevertheless, this system is not suitable to describe the athlete movements such as leg and arm angles of rotation.

3. A CONCEPTUAL APPROACH FOR MONITORING AND EVALUATING OF PERFORMANCE IN ROWING BASED ON MMT

As already stated, most monitoring and evaluation systems in rowing are intended to meet individual goals and to study specific aspects of the problem. Therefore, such systems lack to certain extends integration and rigor in terms of sensor configuration used and level of synchronization as well as the analysis methods applied respectively. As a result, existing systems are mostly concentrating on performance evaluation of certain characteristics in rowing rather than attempting a holistic approach to the problem. This study presents only some very first ideas of a conceptual approach that would attempt to study the problem in a more or less integrated manner.

Figure 3 depicts a generic flowchart scheme that outlines the rowing problem in terms of a "*cause-effect*" relation. In this presentation, the boat kinematics (*effect*) which is of final interest in rowing, represents the synergy result of the three sub-systems that define the rowing system – the athlete, the rowing equipment and the environment (*causes*). In this operating scenario the boat kinematics can be quantified using a suitably designed mobile mapping system featuring position and navigation sensors. On the other hand the biomechanical factors (or at least a selected subset of them) that affect the rowing system can be measured using various sensors such as dynamometers and goniometers. It is proposed that analysis of the recorded biomechanical parameters potentially would lead to the computation of boat kinematics allowing for a direct comparison against measured kinematics. As a result the knowledge obtained from this comparison it would be used for feed-back analysis and model calibration as a means to optimize its end results. At this stage the biomechanical modeling method is still unclear. However, alternative approaches that would rely on artificial intelligence and other techniques are under consideration. Environmental effects shall be taken into account as the modeling scenario evolves. In conclusion, it is anticipated that this research would formalize a procedure suitable for evaluating rowing performance by simultaneously analyzing on-water kinematics and biomechanical data. Besides, it would attempt to propose a set of meaningful and reliable indices to characterize efficiency in rowing under certain circumstances.

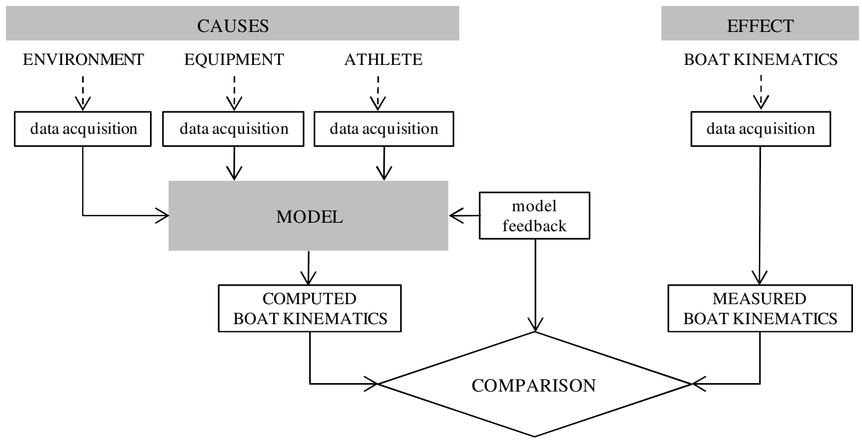

Fig. 3. Cause-effect relationship among biomechanical factors affecting rowing performance

Clearly, being an integral part of this research effort, an integrated and reliable acquisition system deemed necessary in order to obtain on-water data for further analysis. Table 1 contains some base information of the measurements and type of sensors that such a system should employ.

Tab. 1. Measurement types and mapping sensors used to record rowing biomechanics

System	**Subsystem**	**Sensor**	**Measurement**
On-Board Data Acquisition System	Athlete	Goniometer	Joint angles
	Boat Equipment	Position Transducer	Seat position
		Potentiometers	Oar vertical angle
			Oar horizontal angle
			Oar rotation
		Load Cell	Forces transported to hull
		Strain Gauge	Handle Force
		Force Plate	Feet force
	Boat	GNSS receiver	Boat Kinematics
		INS (gyroscopes, accelerometers)	Boat attitude
		Video based systems	Image / Video Documentation
Land Data Acquisition System	Environment	Thermistor	Air Temperature
			Water Temperature
		Magnetic Switch	Wind Speed
		Potentiometer	Wind Direction
	GNSS Base	GNSS receiver	GNSS corrections

4. PRELIMINARY TESTING AND RESULTS

At this stage preliminary testing and investigations is undertaken in order to study the boat kinematics and the nature of their error sources. Pre-processing of the raw navigation data involves elimination of their noise effects and removal of outliers. Using the pre-processed (clean) data, average stroke values can then be computed. This information represents the variation of boat kinematics after the local (stroke cycle) effects have been removed from the raw (pre-processed) data. Further analysis would suffice to compute the typical stroke cycle as a means to evaluate rowing technique. Also, this part of the analysis facilitates the study of statistical correlations between the various types of boat kinematics. In essence, the ultimate goal of this analysis is to study the nature of boat kinematics in order to produce base results that can be used for an in depth biomechanical modelling.

To this effect, an elementary data acquisition system featuring an L1/L2 GPS receiver (Javad, 10 Hz) and a GPS/MEMS-IMU unit (MIDG II, 50 Hz) was used to record a number of single scull runs at Shinias Olympic Rowing and Canoeing Center, Greece (Figure 4) [Fotiadis, 2007]. In the following sections some key results from this preliminary testing are outlined. Figure 5 shows the periodogram obtained for a test run using the L1/L2 GPS velocity recordings. From this diagram is evident that the basic stroke cycle pattern is the summation of two frequencies. Notably, the dominant frequency (f=0.332 Hz) represents the mean stroke cycle frequency. Alternatively, this equals with the mean stroke cycle period (T=3.01 sec) which corresponds to approximately 19.3 strokes per minute. Also, from the same diagram the noisy part of the velocity frequency spectrum is evident. Using this information a detailed analysis of the boat velocity is possible. Figure 6 shows three estimates of boat velocity for a subset of a test run. The dotted and continuous lines denote the raw L1/L2 GPS velocity observations and their smoothed (noise-free) estimates respectively whereas, the dashed line represents the mean stroke velocity. In fact, this last estimate maps the variation of mean velocity through time and it can be of practical use for performance evaluation and training purposes.

Fig. 4. GPS and MEMS-IMU configuration used during preliminary testing at Shinias Olympic Rowing and Canoeing Center

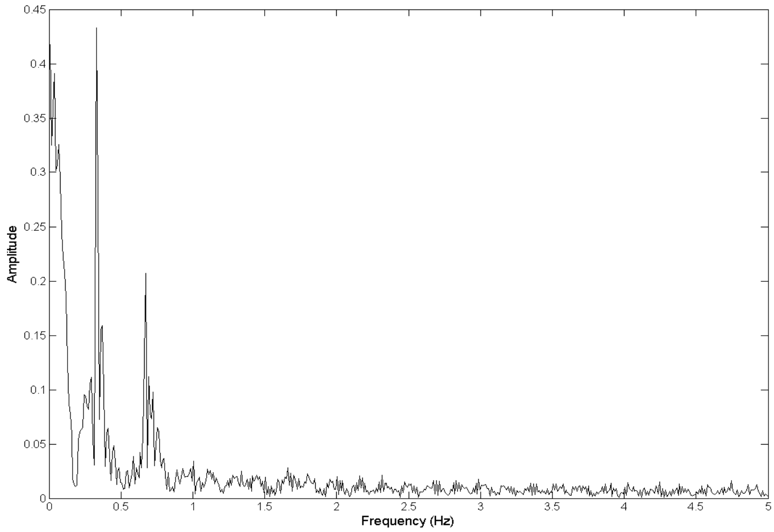

Fig. 5. Periodogram of GPS boat velocity obtained for a subset of a test run

As stated already, boat velocity diagrams contain base information useful for biomechanical modeling purposes. For instance, Figure 7 shows a very simple modeling of stroke distance versus stroke rate. From this diagram it appears that stroke distance increases as stroke rate increases. Of course this general trend could have been predicted from common sense. The advantage of data modeling is that it can be quantified so it can be directly used for assessing of the technique efficiency at different stroke rates.

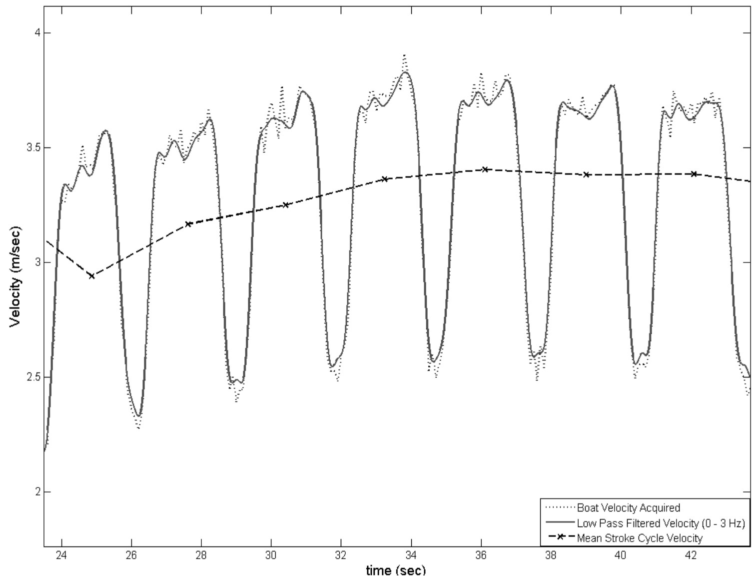

Fig. 6. Raw and computed GPS boat velocity estimates using recordings obtained for a subset of a test run

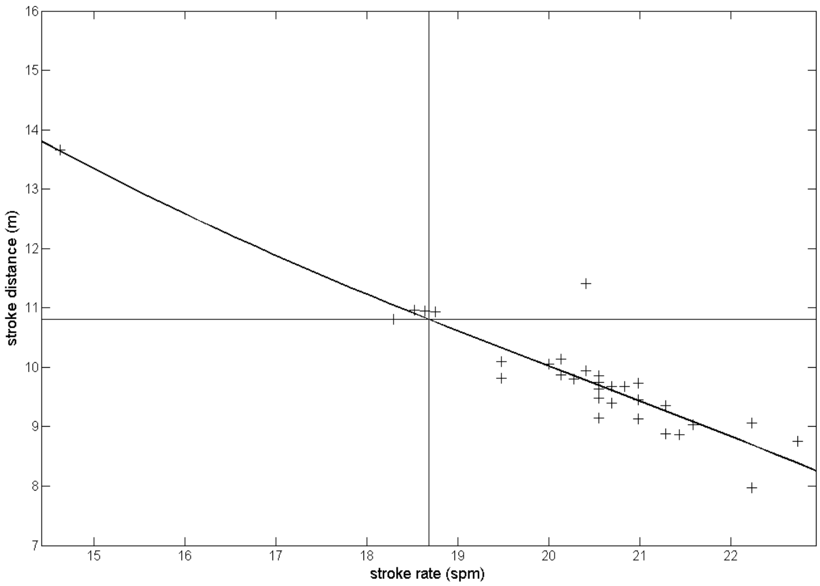

Fig. 7. Example of stroke rate versus stroke distance modelling using a polynomial function of order three

Figure 8 shows as an example the variation of boat velocity and acceleration for a stroke cycle. From this plot the four phases in rowing and the variation of boat velocity versus acceleration is evident. Another example of data pre-processing is given in the plot of Figure 9. In this plot, sudden changes in boat acceleration (see locations I, II, III and IV) coincide with abrupt changes in boat direction (yaw angle). Again, notwithstanding such behaviour is easy to predict by common sense, cross-examination of different data types can be useful for quality control purposes. Similarly, Figure 10 shows some test results of the filtered boat velocity and acceleration (top plot) and boat draught (bottom plot). A detailed examination of these plots reveals some abrupt changes in the velocity variations at location areas I and II. Interestingly, the underlying reason for each of the two cases might be different. In the first case, deviations in boat velocity are most likely due to the rower (ineffective paddling technique) whereas, the latter might be due to an instantaneous failure in GPS signal. Moreover, these results can be explained by examining boat velocity in comparison with boat acceleration and draught. Notably, the MEMS-IMU acceleration pattern is disturbed at location I (but remains unchanged at location II) whereas, the solution for GPS height exhibits an abrupt fluctuation only at location II.

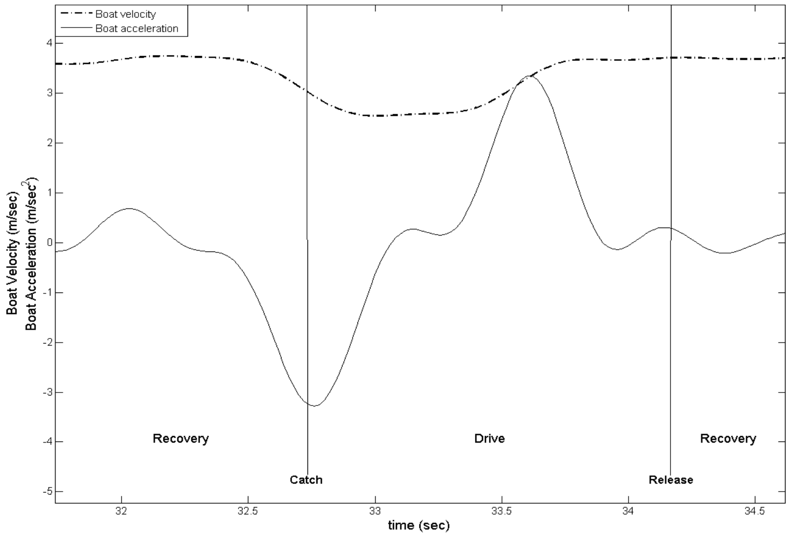

Fig. 8. Example of GPS boat velocity and acceleration variation of a single stroke cycle

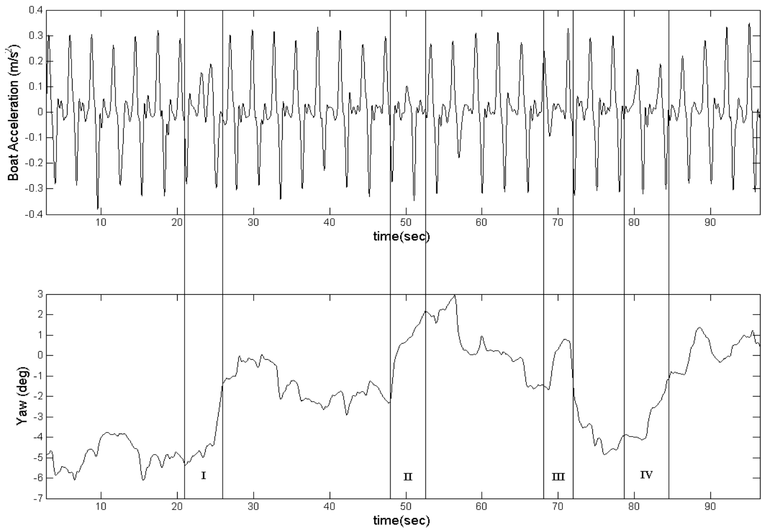

Fig. 9. Cross-examination of GPS boat acceleration versus yaw (MEMS-IMU) obtained for a subset of a test run

Finally, Figure 11 shows the velocity profile obtained from the recordings of two athletes; an experienced (top plot) and a beginner (bottom plot). Clearly, the top plot exhibits that the rower retains boat velocity during finish and recovery, suggesting an efficient stroke cycle. In contrast, in the bottom plot the maximum boat velocity is being lost very rapidly indicating an ineffective rowing technique.

5. CONCLUDING REMARKS

This study deals with the problem of performance monitoring and evaluation in rowing. It examines the biomechanics of rowing in relation to applied technique and offers an overview of existing monitoring sensors and systems. The main interest is however in the potential of MMT – i.e. the various data types, the sensors, their level of integration and limitations. Also, a conceptual approach for monitoring and evaluating of performance in rowing based on MMT is presented. Towards this research direction some example results and their significance in rowing obtained from the processing of preliminary testing are discussed.

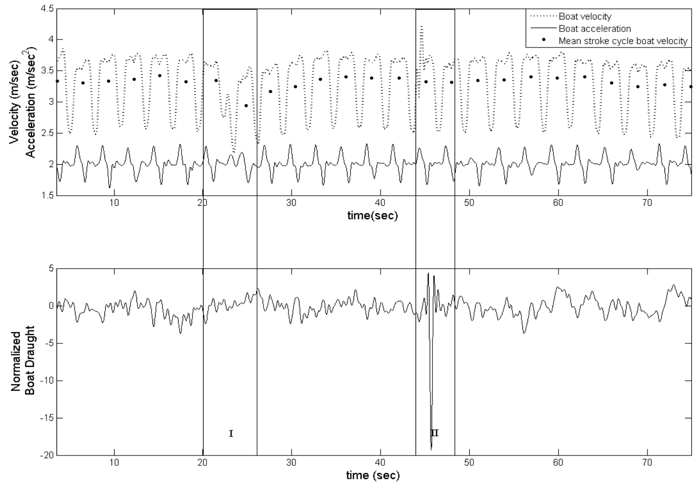

Fig. 10. Cross-examination of GPS velocity and MEMS-IMU acceleration versus GPS derived draught obtained for a subset of a test run

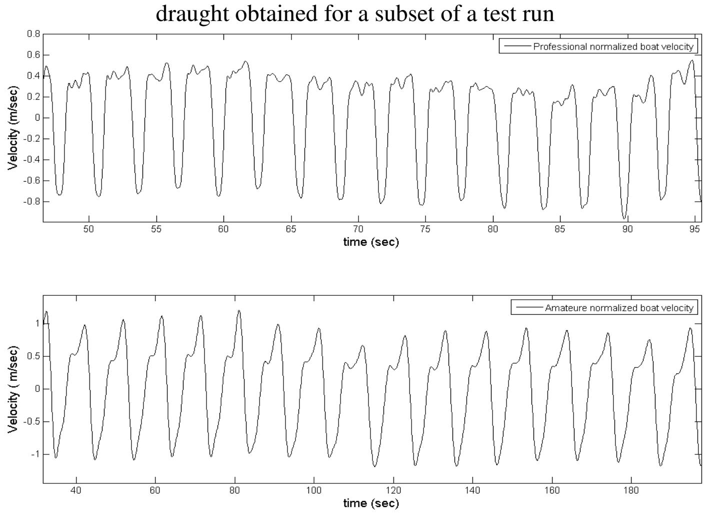

Fig. 11. Example of GPS boat velocity timeseries obtained for two athletes (experienced and beginner)

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