Computational Fluid Dynamics to Reach a High-fidelity Simulator of Performance in Rowing

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Abstract: The massive growth of computational power and the advances of the numerical models make the use of numerical simulations to help analysing and improving sport performance achievable. However, it is still challenging because the physical configurations generally involved complex coupled problems and because human is part of the system. Furthermore, elite athletes already operate near an optimal point. As a consequence, the modelization of all the phenomena that come into play has to be accurate enough to be useful and relevant when the objective is to analyse interactions and to give reliable trends while varying some parameters. The case of rowing is presented here, through the development of SPRing (Simulator of Performance in Rowing), a high-fidelity simulator of the global system "boat-oars-rower(s)" coupled with the resolution of the Reynolds-Averaged Navier-Stokes equations to provide fluid forces acting on it.

1 INTRODUCTION

During the past twenty years, relationship between Centrale Nantes, CREPS des Pays de la Loire and the French Rowing Federation has been forged through various research projects linked to performance support, including experimental campaign in towing tank using specific devices to investigate the flow physics around hull and blades, on-the-water measurements, and numerical validation. With both the upcoming 2024 Olympic and Paralympic Games in Paris and the achievements in HPC and in CFD over the past decade, time has come to capitalize all the knowledge acquired to develop a high-fidelity simulator of the boat-rower(s)-oars system coupled with a CFD flow solver to better understand the physics of this complex mechanical system. Preliminary results look very realistic and promising, and illustrate the relevance of some technical choices which were made. On this basis and before being exploited, a deeper validation step has to be carry out, which is a mandatory but not straighforward prerequisite. The pursued objective of this challenging tool is to help coaches and athletes in the quest of the best performance.

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2 MODEL OF THE GLOBAL SYSTEM BOAR-OAR(S)-ROWER(S)

The global system Boat-Oar(s)-Rower(s), denoted by BOR system thereafter, is considered from a mechanical and inertial point of view as a system composed by a set of rigid bodies (even if deformed by the fluid loads and rower loads, the oars keep their inertia properties unchanged, which is a valid assumption). The mass of the BOR system is conserved in time whereas the global inertia properties (position of the center of gravity and inertia matrix) changes according to the internal degrees of freedom defined by the position of the oars and of the rower(s) with respect to the boat. Once defined the floating frame of reference linked to the boat where the origin is set at the keel line at the middle of the boat (see figure 1), the resolution of the dynamics of the BOR system is then reduced to the resolution of the Newton's law of a system which inertia properties changed in time and subjected to external forces, similar to what is done in (Leroyer and Visonneau, 2005). The external degrees of freedom (DOF) of the BOR system which are solved are namely the position and the orientation of the hull as a function of time: the hull kinematics is thus the output

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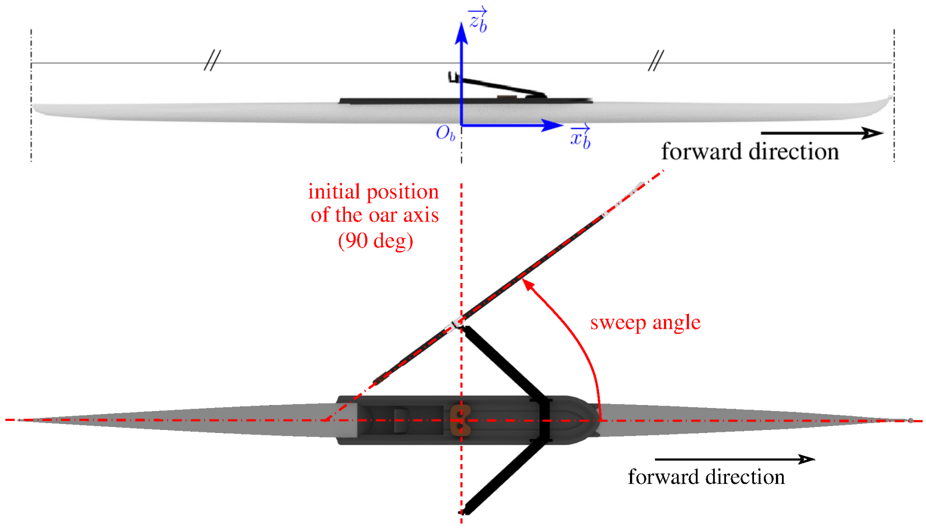

Figure 1: Parameterization of the system.

of the resolution.

Except the gravity, the major part of the external forces, strongly coupled to the BOR system, comes from the hydrodynamic forces acting on the hull and on the blades. To reach an high-fidelity model, they are computed using CFD (see section 3). Other aerodynamic forces which contributions are limited, are taken into account through simplified analytical models. The motions of the rower(s) and of the oars with respect to the boat represent the internal DOF of the BOR system. They are responsible both for the change of inertia parameters of the system and for the propulsive force through the generated hydrodynamic forces. Except the induced deformation of the shaft which are solved together with the resolution of the dynamics of the hull (Robert et al., 2018), all other internal DOF are imposed to reproduce the variety of kinematics found among elite rowers. Details are given in section 4.

3 EXTERNAL HYDRODYNAMIC LOADS AND COUPLING

3.1 Need for High-fidelity CFD Model

More than two decades ago, experimental research works were done to characterize flows involved in rowing, especially around the blade. A specific device was designed and used in a towing tank to reproduce the main characteristics of this violent flow using real oars. This initial goal was to better understand the physics of this flow and to build simplified models (Barré, 1998; Barré and Kobus, 2010). Even if these models can reproduce the right order of magnitude and are useful to quickly test the simulator, they will never be accurate enough to take into account all the subtle interactions which appear during the propulsive phase, especially during the catch phase, which is essential to the propulsive force generation of the whole stroke. Given the high-accuracy requirement to address sensibility analysis to small variations of parameters, it was decided to directly couple the high-fidelity model based on CFD computations using the ISIS-CFD solver to power the fluid forces interacting with the BOR system (on the hull and on the blade), without any compromise in accuracy (Robert et al., 2018). In this challenging task, this unique experimental database turned out to be of great help to validate the CFD tool (Robert, 2017; Robert et al., 2018). Such a work has never been reported in the literature. (Formaggia et al., 2009) coupled a simplified 6 DOF model of the BOR system with a CFD flow resolution around the hull while imposing analytical law of fluid loads for the blades. (Sliasas and Tullis, 2009; Sliasas and Tullis, 2010) coupled a 1 DOF model of the BOR system with CFD flow resolution around the blade (without taking into account either vertical motion or shaft flexibility) and while using an analytical drag-based hull velocity model: results exposed in (Sliasas and Tullis, 2009) seem somehow nonphysical, especially when the propulsive force become unexpectedly negative at the end of the drive phase but which, oddly enough, does not appear in (Sliasas and Tullis, 2010). Shaft flexibility is investigated separately without coupling with a BOR system in (Sliasas and Tullis, 2011) , but using a one-way coupling then requiring to repeat several times the simulation to converge.

3.2 ISIS-CFD Solver

ISIS-CFD is an incompressible unsteady Reynolds-Averaged Navier–Stokes (RANS) solver developed by ECN-CNRS, available as a part of the FINE^{TM}/Marine computing suite which is dedicated to marine applications. This solver is based on a cell-centered unstructured finite-volume method. Advanced capabilities such as fluid structure interaction, automatic adaptive grid refinement technique and overlapping grid technology are required in the present context to achieve both accurate and efficient computations. This worldwide used tool has been validated through various CFD workshops in ship hydrodynamics (Deng et al., 2012; Deng et al., 2015; Queutey et al., 2021). As previously mentionned, a hard validation work has also been carried out for the specific flows involved in rowing using previous experimental research works on this topic (Barré, 1998; Barré and Kobus, 2010; Robert, 2017; Robert et al., 2018).

3.3 Co-simulation between ISIS-CFD and SPRing

To reach an efficient and robust algorithm for this partitioned approach, the coupling iteration is done within the non-linear iterations of the fluid solver. This implicit internal coupling solves both the dynamics of the hull and the deformation of the oar shafts computed by SPRing (Simulator of Performance in Rowing) using the current fluid loads and then update these kinematic modifications to the fluid part. The model of flexibility of the shaft is based on a beam model with a variable stiffness law along its length. The parameters of this law has been calibrated using a specific flexibility test bench for oars, which is not described here.

Data transfer between the two codes is done through a TCP/IP socket-based protocol, using the ZeroMQ distributed message library (Akgul, 2013). As other fluid-structure interaction in hydrodynamics, a stabilization procedure based on an artificial added mass method is used to tackle the destabilising added-mass effects (Yvin et al., 2018).

4 CONTROL OF THE INTERNAL DOF

As previously described, the internal DOF of the BOR system are given by the position of the oar and the position of the rower. In most of research works involving a model of rower, a kinematic control (time

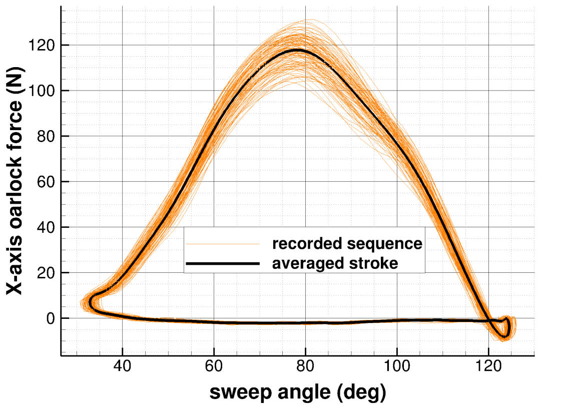

Figure 2: Force as a function of sweep angle, raw data and averaged procedure.

law of join angle (Cabrera and Ruina, 2006; Rongère et al., 2011) or a dynamics control (time law of join torque (Pettersson et al., 2014)) is used to drive the posture of the rower in time and induce the motion of the oar. Here it is done in the opposite way: the sweep angle of the oars as well as the vertical height of the blade with respect to the water surface are imposed in time. The main motivation of this choice is the ease to reproduce real crews since the sweep angle is a data which is available at each on-the-water measurement. It also offers the possibity to modify the rowing stroke by modifying the temporal law of the sweep angle. The vertical position of the blade is far much tricky to track in-situ. At that time, this data is not yet measured. However, thanks to video analysis, a parametric model can be built to reproduce as accurate as possible the real path, as described in section 4.2. Technical gesture which identified each rower, called here gesture signature, is reproduced through some parametric curves driving the athlete position.

4.1 Oar Motion Input

Sweep angle is given as a time series. When dealing with an on-the-water measurement during a sequence at constant stroke rate, an averaging procedure is applied to work with a pure periodic signal, see figure 2. A synthesis procedure has been developed too, which enable to create a B-spline based parametric model of the sweep angle and then to play with the parameters to modify the rowing stroke. An illustation of this fonctionnality is given in section 5.

Vertical position of the blade is modeled by a set of 16 parameters for the whole stroke: twelve of them are dedicated to define both the catch phase (see figure 3) and the release phase (see figure 4). The others are dedicated to model the link between these two phases.

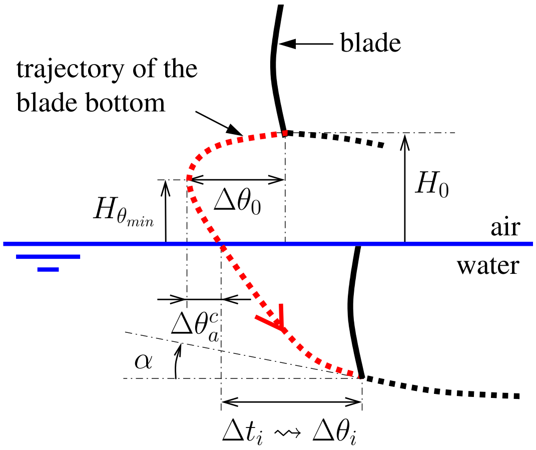

Figure 3: Parametrization of the vertical motion of the blade during the catch phase.

H_0: blade height with respect to the water at the beginning of the catch phase,

$\Delta\theta_0$: starting sweep angle of the catch phase minus minimum sweep angle,

$H_{\theta_{min}}$:blade height at minimum sweep angle,

$\Delta\theta_a^c$: angular deviation before immersion,

Δt_i: immersion time,

α: slope of immersion at the end of the catch phase. of immersion.

4.2 Rower Gesture Signature

Even if this is not what's happen in real life, the whole motion of oars is imposed using the input data and model described previously, and the rower moves accordingly. However, for a given position of oars, there is multiple rower positions satisfying the constraints (hands attached to handles, foot attached to the stretcher and buttocks following the sliding seat path). The temporal evolution of limbs position satisfying the constaints define the gesture signature. To reproduce a variety of gesture signatures, evolution of legs bending, trunk inclination and arms bending are driven through parametric curves, function of their respective stretching ratio at the current posture. The temporal evolution of the rower position is then computed incrementally : at each new time step, the stretching ratio are used to find the contribution of each part of the rower body involved in the oar position increment, as shown in the figure 5 at the left. The resulting rower kinematics is shown at the right. As an illustration, it can be seen that at the end of the driving phase as well as the beginning of the recovery, arms are the limbs which is mainly responsible of the oar motion whereas around the catch phase, the oar motion is mainly due to the modification of legs bending. Some additional features, such as spine curvature, lift of the heels and strech of the shoulders close to the catch, have also be implemented to enrich the gesture signature. Special care need to be done for the whole kinematics which is imposed. Sweep angles, blades height and limbs motion have to be defined with smooth enough temporal series (equivalent to functions of class C^2) to obtain a smooth response of the hull dynamics. Other input data as density and geometry of each members of the rower are mainly based on the work described in (Yeadon, 1990) and (Leva, 1996), and set them according to the rower morphology.

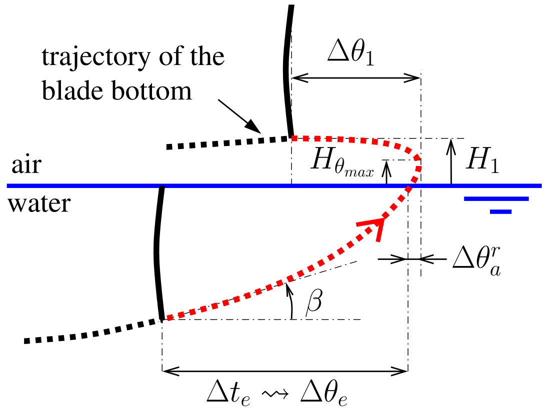

Figure 4: Parametrization of the vertical motion of the blade during the release phase.

Δt_e: exit time,

β: slope of exit at the beginning of release phase

$\Delta\theta_a^r$: angular deviation after exit,

$H_{\theta_{max}}$:blade height at maximum sweep angle,

H_1: blade height with respect to the water at the end of the release phase,

$\Delta\theta_1$: maximum sweep angle minus final sweep angle of the release phase.

5 RESULTS

A first preliminary simulations have been carried out using a quite coarse mesh of around 2 million cells to provide a proof-of-concept. An initial phase starts with a speed-up of the hull using an imposed forward velocity ramp up to a guess velocity while keeping solving heave and pitch (see figure 6). In the meanwhile, the rower moves from his initial position (sweep angle 90°, fully stretched legs, vertical trunk) to the catch phase with a smooth kinematic connection at the configuration when the height of the blade reaches its maximum value. This connection is done at the time when the whole resolution of the dynamics starts.

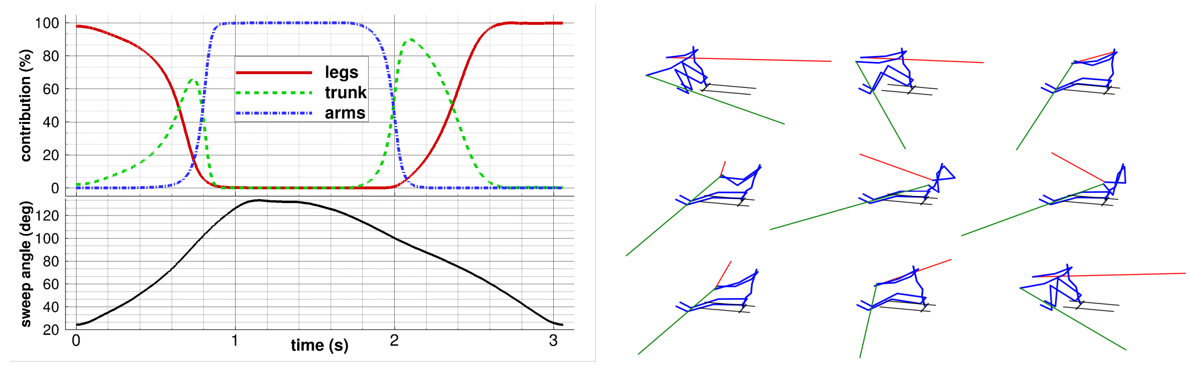

Figure 5: On the top left, contribution of legs bending, trunk inclination and arms bending to the oar rotation as a function of time, resulting on the incremental procedure. On the bottom left, averaged sweep angle as a function of time coming from measurement. On the right, resulting sequence of rower postures for a whole rowing stroke.

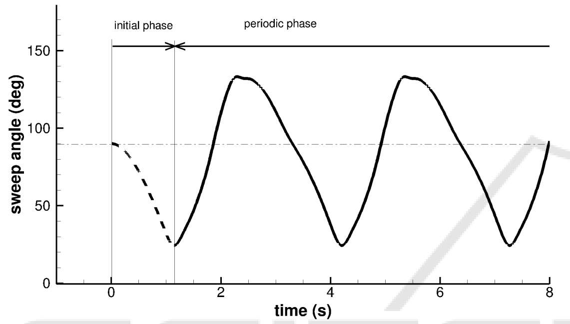

Figure 6: Imposed sweep angle as a function of time including the initial phase.

A specific Graphical User Interface (GUI) has been developed to set all the input parameters, from the generation of the periodic sweep angle to the morphology of each rower (see figure 7).

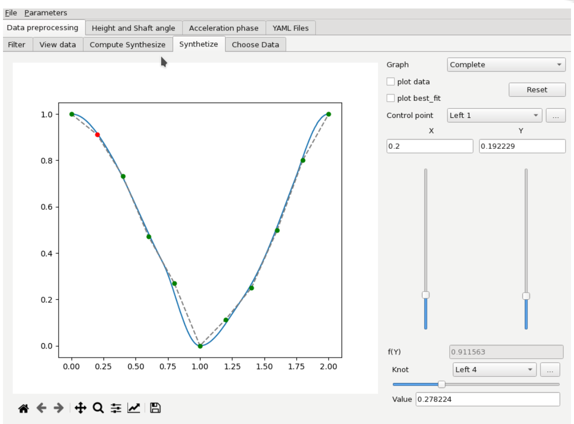

Figure 7: SPRing input GUI showing the synthesis of a given sweep angle with B-spline.

Considering the final objective of the tool, an important aspect of the project concerns the realistic rendering of the simulation, see figure 8. It has

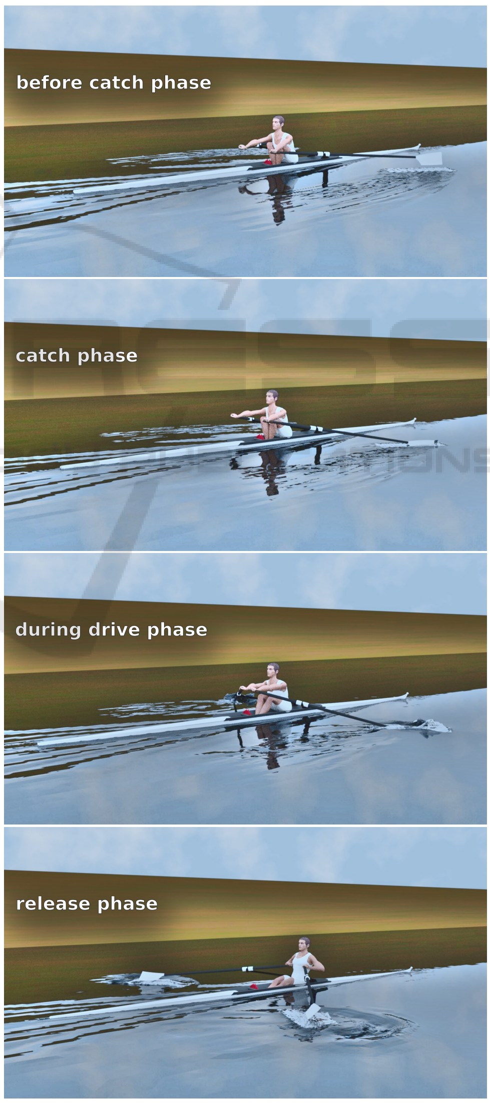

Figure 8: Realistic rendering of the co-simulation SPRing/ISIS-CFD. Computed free surface are imported from CFD simulation as STL triangulation.

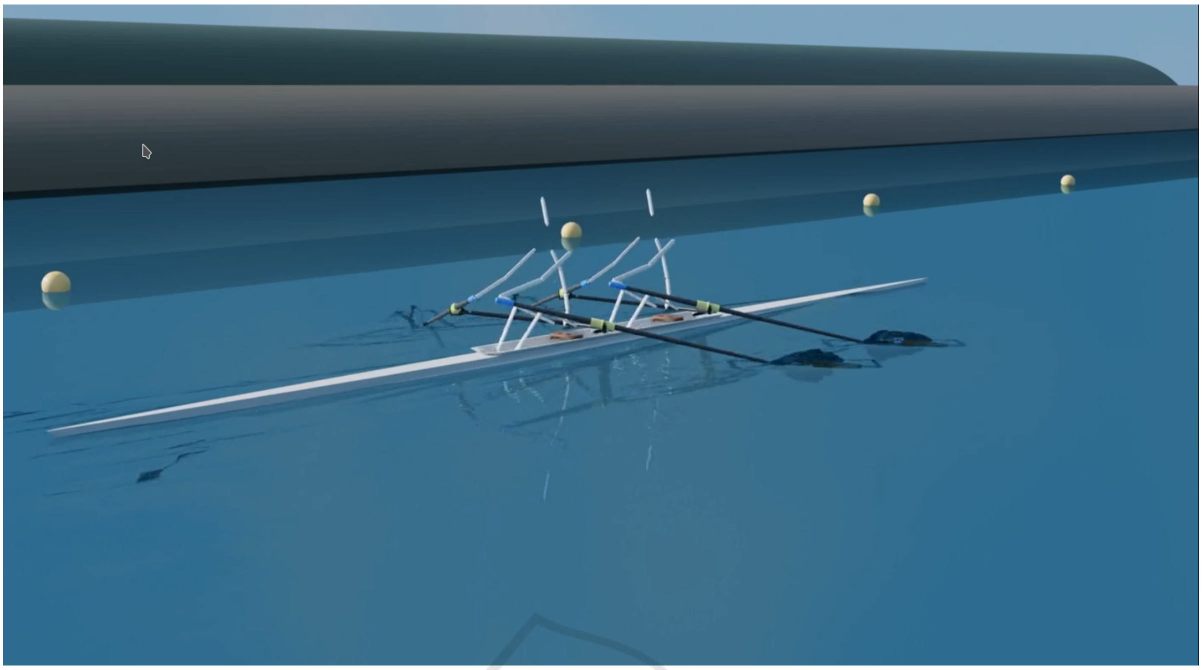

Figure 9: Stickman rendering of a double skull with a co-simulation SPRing/ISIS-CFD. Morphology and gesture signature can be defined specifically for each rower.

been developed using the open-source Blender software (Community, 2018). Such a post-treatment is important as a communication facility with coaches, but also to easier confront the reality with the simulation. However, due to the complexity to fit automatically the human mesh with the morphology of each rower, this approach has been put aside at the moment in favor of a less realistic "stickman" representation of rowers, see figures 9 and 10. This fully automatic mode, still using Blender, is driven through another dedicated GUI. Specific outputs (hull kinematics, oar deformation, incident velocity around the blade,...) can be visualized through synchronized graphs or by superimposed arrows in a multi-view scene, which greatly facilitate the physical analysis too.

6 CONCLUSION AND PERSPECTIVE

To achieve the scientific challenge of a high-fidelity model of the BOR system, a multi-body system has been developed to accurately model the kinematics of the rower with respect to its environment. It is the next step after previously published reference CFD results (Robert et al., 2018; Robert et al., 2014), on which it relies. This imposed kinematics is driven both by some gesture parameters and time evolution of sweep angle of each oar (which can be provided from in-situ data measurements) and height of the blade with respect to the free surface. The dynamics of the global system is then reduced to the dynamics of the hull, which is solved by integrating the major fluid forces acting on both the hull and the blades through CFD resolution (Robert et al., 2018; Robert et al., 2014). The original kinematic approach of the control of the gesture signature has been motivated to be in line with the objective to have both an accurate description and the most operational tool to analyse and serve performance in rowing. Before playing this role, an extensive step of validation for these coupled simulations needs to be investigated using on the water measurement. This validation step is crucial because Science can bring a new insight on sport performance, only if the model lives up to the expectations in term of accuracy so that the physical analysis of the phenomena can be trustingly carried out. The preliminary results obtained with the high-fidelity co-simulation look very realistic and is a source of motivation to pursue this path. In parallel of that, more advanced mechanical analysis (load on human joints, power consumption, efficiency,. . .) is planned to benefit from all the data which are computed. At term, such tool targets to bring objective and unbiased criteria for questions which have only empirical answer up to now.

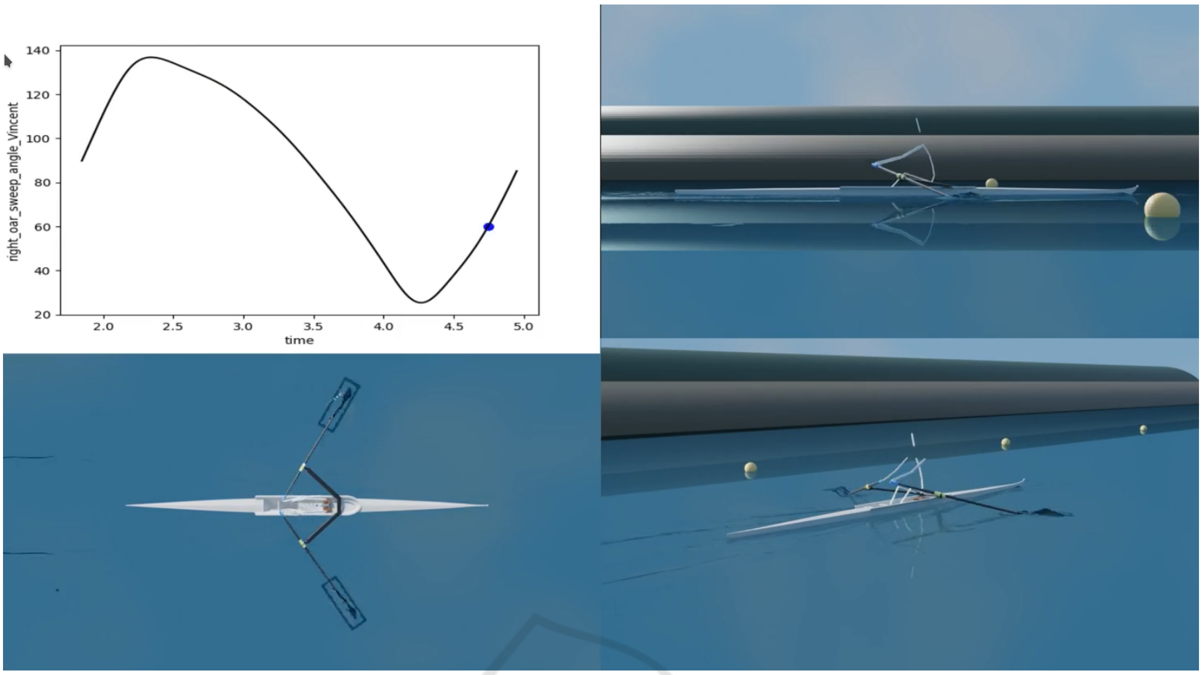

Figure 10: Multi-view stickman rendering, synchronized with the graph showing the sweep angle as a function of time, made by the SPRing output GUI.

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