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A coupled biomechanical-Smoothed Particle Hydrodynamics model for predicting the loading on the body during elite platform diving

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ABSTRACT

Platform diving injuries are common, especially in the arms, neck and back, and appear to arise from cumulative damage from multiple overload events as well as singular cases of acute loading. Experimental measures of forces on the body are impractical so instead computational simulation is used to estimate this loading. A coupled Biomechanical-Smoothed Particle Hydrodynamics (B-SPH) model for diver and water is developed and applied to a reverse pike dive performed by an elite athlete. The body surface is represented by a mesh that deforms in response to measured skeleton kinematics acquired from multi-camera video. Calculations of the fluid forces on the body and the transmission of torque through the upper body joints are made. Loading on the body segments and joints is found to be closely related to the dynamic behaviour of the body and water. The sensitivity of the results of the model to variations in water entry pitch angle (EPA) is explored. Simulation results suggest that altering the timing of contact between the water and different body segments changes the loading and potentially the injury risk of the dive. The simulation framework presented shows promise as a tool for coaches and sports scientists to evaluate the performance, strength requirements and safety of diving technique.

1. Introduction

Platform diving is a sport which has an inherent risk of injury with the greatest incidence occurring during water entry [1–3]. They can be either the result of catastrophic overloading of joints during a sub-optimal dive or from an accumulation of damage from repetitive low intensity loading [1,4]. Common sites of injury are the wrists, shoulders, neck and lumbar spine [1,2,5–11,4]. The pose of the upper body is usually considered to be a determining factor for the risk of dangerously high loading of these sites during water entry [3], however the relationship between joint load and body position has not been quantified.

In order to understand how injuries occur, it is advantageous to have detailed information about the mechanical loading of the body and its joints during water entry and the subsequent drag dominated interaction with the water. Little quantitative data about the loading of the body during water impact and its transmission through the muscular-skeletal system is available because

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direct experimental measurement of loading on the body surface, joints and bones is not possible. Biomechanical analysis of this complex interaction is sparse and primarily qualitative [1,12,13,10,11]. Kinematics studies by Brown et al., [12] and Hamill et al., [13] correlated angular momentum during the aerial phase and the type of water entry (rip entry or non-rip entry) to particular aspects of technique such as arm rotation. Le Viet et al., [6] presented a brief analysis of acceleration differences between dives from different heights to suggest why high platform dives cause a large number of injuries. However, no study to date has been able to experimentally measure the loading on the body or the differences in loading for different dives or mistimed dives.

Strong externally generated joint torques are useful indicator of large internal forces and appear to be correlated to the risk of injury in physical activities (e.g. [14]). Large torques relate to injury because muscles must activate to counteract external torques and the resultant joint contact force can be many multiples of the total external force [15]. Large muscle and external forces can dangerously load articular surfaces, ligaments, bones and muscles, leading to an increased risk of injury.

Computational modelling including biomechanical elements has previously been useful for identifying causes of injury for non-aquatic sporting activities. They allow prediction of the mechanical loading on joints, muscles, bones and connective tissue. In particular they allow prediction of surface stresses; net joint torque, joint power, joint, muscle and tendon forces and articular stresses allow these to be determined on for different body segments. Examples include the effect of injury from falls [16] and from running [17].

Simulation has previously been used to evaluate the flight phase of platform diving [18–20]. Studies to date into the fluid response and forces on the body during diving have involved large simplifications, such as modelling the hands as wedge shaped objects [21]. No models have been developed that accurately represent the geometry of the athlete, their motion or their deformation during the dive, or the fluid forces imparted onto their body during and after entering the water from a dive. Modelling of full body–fluid interaction during water entry presents several key challenges. The free surface of the water undergoes large displacements with significant amounts of splash being generated. The surface of the diver also deforms significantly during diving as their pose varies dramatically with the different phase of jump, spin, somersault, tuck and straightening for entry. The speed of the diver at entry is also large. All of these issues cause strong difficulties for grid or based fluid dynamics methods. In contrast, SPH is a particle method that is well suited to transient fluid dynamics problems which involve complex free surface behaviour and moving and deforming boundaries of complicated shape. Since the method is Lagrangian the strong advective components of the flow are handled automatically. Its mesh-free nature allows the use of boundary structures (representing the diver) which vary significantly in shape and avoids issues relating to deterioration in mesh quality resulting from significant deformation of the fluid. Examples of SPH applied to such complex geometry and splashing flows are given in Monaghan [22,23]; Cleary et al. [24–26]; Crespo et al. [27]; Oger et al. [28] and Souto Iglesias et al. [29]. It has recently been used in equally challenging modelling of oral digestion that [30,31]. Cummins et al. [32] demonstrated the accuracy of the SPH method for fluid-structure interactions with detailed comparison of the force transmitted to a column from a breaking wave. SPH has also been successfully applied in an aquatic sports context to simulate elite swimming [26,33–36].

In this paper, a computational framework is presented for predicting performance and injury for competitive platform. This uses a coupled biomechanical-Smoothed Particle Hydrodynamics (B-SPH) model. The model is used to explore three critical issues around diving performance and injury:

1. What forces are imparted to the human body during water entry at the end of a dive and how does this vary between different parts of the body?
2. What torques are generated in the arm, neck and back joints during water entry?
3. How does the pose and motion of diver's body once underwater affect the fluid forces generated and the resulting loads and torques on the body?

A female Australian Olympic athlete performing a reverse pike dive is used for this study. Their in-air and underwater motion was digitised and used to deform digital representation of her body obtained by laser scan. Simulations for 5 and 10 degree errors in the angle of entry were performed to evaluate the dependence of the body forces and torques on the degree of under or over-rotation. The resulting body motion, fluid forces on body segments and net torques about the joints are presented and analysed in the context of understanding the resulting injury risk. The suitability of such a model for injury prediction purposes is evaluated. Preliminary results of this model were presented in Harrison et al. [37].

2. Methods

2.1. Computational model

The proposed computational framework is comprised of three coupled sub-models:

1. A biomechanical model of the athlete, which relates the skeletal kinematics of the athlete to the instantaneous geometry of their skin surface;
2. A computational fluid dynamics model, using SPH, that describes dynamics of the water in the pool including free surface behaviour and splashing; and
3. A coupling treatment of the fluid-structure interactions between the water and the diver.

Here we detail the basis of each model and the coupling between them.