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Analysis method of energy transfers between the diver and the diving board

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Résumé : (16 gras)

Cet article propose une étude énergétique de la synchronisation entre le plongeur et plongeoir en plongeon sur tremplin. Cette étude se base sur des données de capture de mouvement de plongeurs, un modèle par éléments finis du plongeoir et un modèle biomécanique du plongeur. Ces modèles sont rendus spécifiques au plongeur et au plongeoir étudiés expérimentalement. Une méthode de prédiction des efforts d'interaction entre le plongeur et le plongeoir est également utilisée. L'ensemble de ces outils permettent de déterminer les quantités nécessaires pour réaliser l'étude énergétique proposée. Cette étude a pour but de mieux comprendre comment s'opèrent les échanges d'énergie entre le plongeur et le plongeoir et de fournir ainsi des outils permettant de savoir comment améliorer les techniques observées.

Abstract : (16 gras)

This article presents an energetic study of the synchronization between the diver and the diving board in springboard diving. This study is based on the motion capture data of dives, a finite element model of the diving board and a biomechanical model of the diver. These models are made specific to the diver and diving board studied experimentally. A prediction method of the interaction efforts between the diver and the diving board is also used. These models and methods are used to compute the features required for performing the presented study. This study aims at better understanding how energy transfers are carried out between the diver and the diving board and providing insight into how improve the observed techniques.

Mots clefs : human-structure interaction, synchronization, performance

1 Introduction

Springboard diving performance comes from the interaction between an athlete and a deformable structure. The energy transfers between the diver and the diving board can be optimized by improving time synchronization [11]. The studied diver and diving board must be modelled to compute the temporal evolution of their energies [15]. A finite element model of the diving board weakly coupled with a biomechanical model of the diver are presented. The interaction efforts between the diver and the diving board are estimated. These models and methods are based on motion capture data. [3].

Previous studies were focused on springboard diving performance. Some of them study the impact of different techniques and fulcrum settings on performance using dive videos [7, 6]. Most of these studies models the diver and/or the diving board to simulate their behaviours. The diver was often modelled as a rigid body system [2, 15]. The diving board was often modelled by a mass-spring system with one degree of freedom, a rigid bar articulated at its origin [2], or a beam with with 3 degrees of freedom in the plan [15]. All these studies enabled to better understand the factors affecting springboard diving performance, mainly at the beginning of the last contact phase before takeoff (touchdown) and at takeoff (diver's velocities, diver's angular momentum, diver's posture, synchronization with the diving board motion). Nevertheless, further studies about the synchronization between the diver and the diving board may be useful for knowing more about energy transfers optimization during the contact phase between the diver and the diving board [12].

Our study, which is based on that of [1], is focused on energy transfers between the diver and the diving board. The studied features are computed from a finite element model of the diving board and a biomechanical model of the diver. These models are based on the motion capture data of dives.

2 Methods

2.1 Experimental procedure

The motion capture data were recorded with the optoelectronic system Qualisys (12 12-Mpixels OQUS 7+ cameras, 200 Hz). 1 male recreational diver (1.65 m, 68 kg) was equipped with a set of 45 reflective markers placed on standardized anatomical landmarks as recommended by the International Society of Biomechanics [13, 14]. Fifty reflective markers were placed on the diving board sides (49 evenly spaced on one side, the last one on the other side at the diving board free end).

A static trial of the diving board without any load, named reference trial, was recorded. It provided the reference vertical position of each marker. The subject performed 2 dives with a running approach (RA dives) and 2 dives with a starting position at the diving board free end (SP dives).

2.2 Simulation of the behaviour of the diver and the diving board

The method used to simulate the behaviour of the diver and the diving board was based on a weak coupling between a finite element of the diving board and a biomechanical model of the diver. The method overview is presented in the Figure 1. These models were based on motion capture data. The biomechanical model of the diver was developed in the Matlab (Release R2021a, MathWorks, Inc., Natick, Massachusetts, United States) toolbox CusToM [10]. The diver model was used to estimate the interaction efforts between the diver and the diving board for the recorded trials. The finite element model of the diving board was developed in the Matlab toolbox ATL4S [5]. The estimated interaction efforts were applied to the diving board model to simulate its dynamic response. A characterization method of the diving board model was used to determine the model parameters leading to a numerical displacement as similar as possible to the experimental one.

The diver was modelled by a rigid body system with 18 segments and 44 degrees of freedom. A geometrical calibration of the model was performed using the studied trial data and the method described in [9]. The body segment inertial parameters were computed using the method from [4]. For each trial, an inverse kinematics step was carried out to compute the joint coordinates of the model.

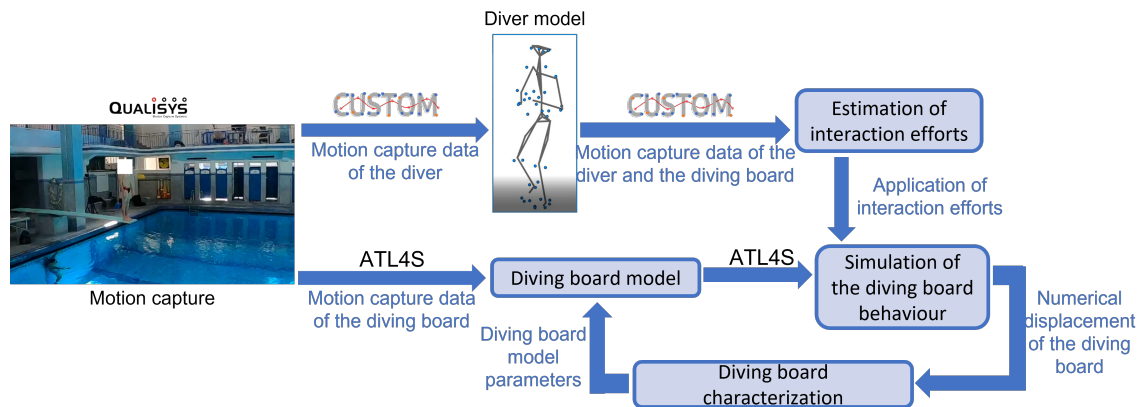


FIGURE 1 – Method overview

The interaction efforts between the diver and the diving board were computed using a ground reaction forces and moments prediction method suitable for the interaction between a human subject and a deformable structure [3]. This method detected the potential contact surface between the diver's feet and the diving board at each frame. The interaction efforts were computed using an optimization method minimizing the quadratic sum of the forces applied under the subject's feet constrained by the dynamic equilibrium of the subject [8].

The diving board was regarded as a uniform and isotropic 2D Bernoulli beam with small deflection and was modelled as shown in Figure 2. The contact at fulcrum at $x = L_1$ was unilateral. The interaction

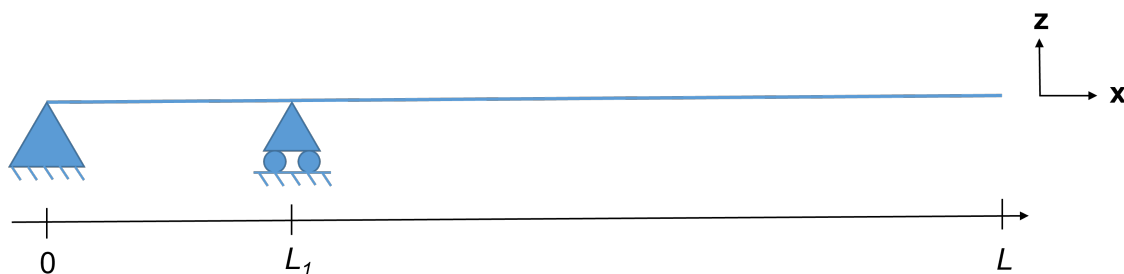


FIGURE 2 – Diving board model

efforts were applied on the node of the diving board model closest to the center of pressure under the diver's feet at each frame. The diving board model was characterized using an optimization method minimizing the normalized sum of the mean squared errors between the numerical and experimental vertical displacements for each observation point of the diving board.

2.3 Energetic analysis of the interaction between the diver and the diving board

Diver and diving board models specific to those studied experimentally and interaction efforts between the diver and the diving board were obtained for each trial using the method and models described above. The temporal evolution of potential, kinetic and mechanical energies of the diver and the diving board were computed using these models and methods.

The computed energies were used to perform an energetic study similar to that of [1] for pole vaulting.

The recorded dives were studied from the maximal altitude of the centre of mass of the diver (CoM) before touchdown and the maximal altitude of the CoM after takeoff (Figure 3).

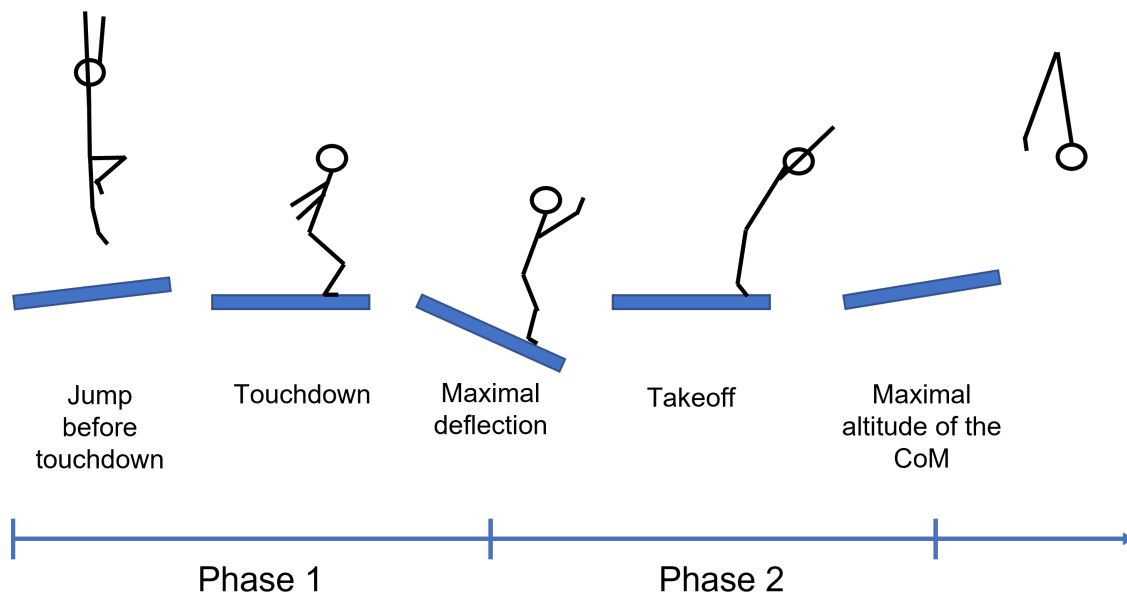


FIGURE 3 – Details of dive phases

The following features were computed for the 4 recorded dives :

- Potential, kinetic, and mechanical energies of the diver and the diving board ;
- Mechanical energy coming from the muscular work of the diver during phases 1 and 2, respectively E_{inp1} and E_{inp2} ;
- The subtraction between the diver's mechanical energy at takeoff and the diver's mechanical energy at his maximal altitude during the jump before touchdown (initial energy) E_{diff} ;
- Moments of each step described in the Figure 3 computed from experimental data.

These features enable to know if the muscular work of the diver created or dissipated energy during the different phases (E_{inp1} during the phase 1, E_{inp2} during the phase 2, E_{diff} between the beginning of the studied period and the takeoff).

3 Results

The studied features are presented in the table 1 for the 4 recorded dives. All the results show that the

Dives	E_{inp1} (J)	E_{inp2} (J)	E_{diff} (J)
SP 1	-109	479	236
SP 2	-108	380	148
RA 1	-113	720	370
RA 2	-66	678	370

TABLE 1 – Energetic features values for the 4 recorded dives

diver's muscular work lost energy during the first phase and created energy during the second phase for all the dives. For a given dive, the amount of the energy created by the diver during the whole studied period, and during each phase, is in the same order of magnitude.

The Figure 4 presents the temporal evolution of the mechanical energies of the diver and diving board for the dive RA 1. After the touchdown, the mechanical energy of the diver was transmitted to the diving

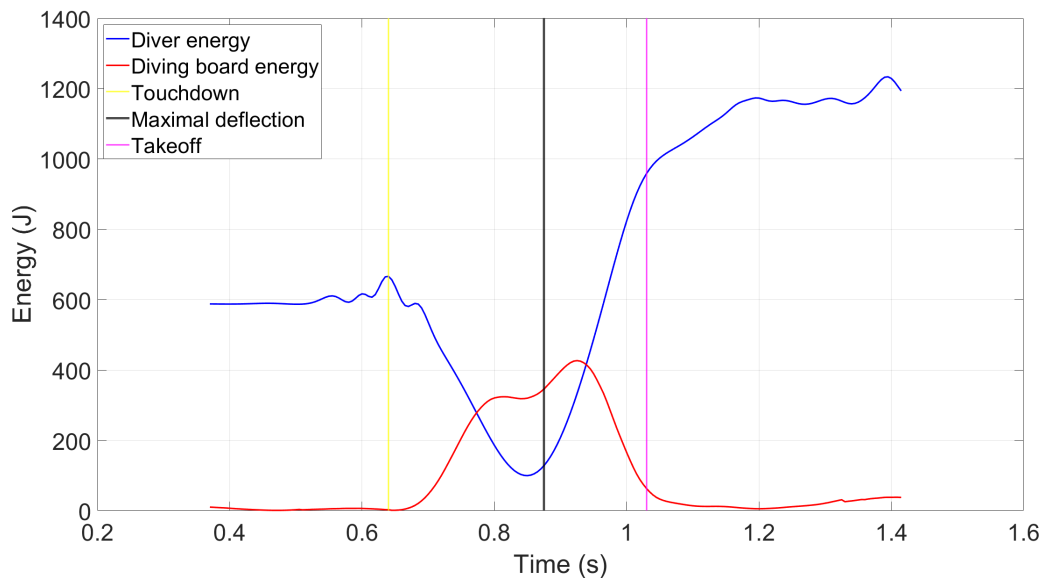


FIGURE 4 – Mechanical energies of the diver and diving board for the dive RA 1

board until its maximal deflection. The mechanical energy of the diving board was then given back to the diver until his takeoff.

The Figure 5 presents the temporal evolution of the potential, kinetic and mechanical energies of the diving board for the dive RA 1. One can observe that the mechanical energy of the diver is stored into

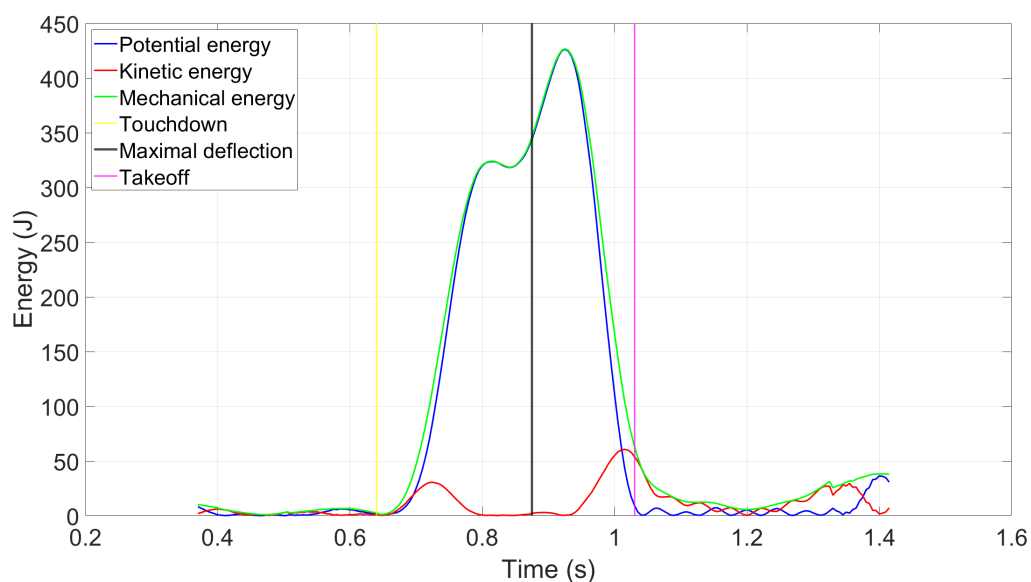


FIGURE 5 – Potential, kinetic and mechanical energies of the diving board for the dive RA 1

the diving board as potential energy between the touchdown and the maximal deflection of the diving board.

4 Discussion

The methods presented in this study are suitable to study energy transfers between the diver and the diving board using motion capture data. A study of work done by the diver to gain height during a 105B dive (similar to the studied RA dive) was performed in [11]. This work was considered as the gravitational potential energy of the center of mass of the diver. An increase of the the diver's energy between the touchdown and the takeoff of 4.3 J.kg^{-1} was observed in [11]. In our study, the variation of the mechanical energy of the diver between the touchdown and the takeoff was also 4.3 J.kg^{-1} . Our results seem to be consistent with those from the literature.

The features E_{inp1} , E_{inp2} and E_{diff} are useful for quantifying the impact of the diver's muscular work for different dive phases. This information coupled with a qualitative analysis of the dive may help to better understand springboard diving performance. To compare these features for several iterations of the same dive performed by the same diver may be useful for identifying deficits or strengths of the studied diver during the interaction phase with the diving board. These data may also help to compare techniques of several divers for a given dive. These methods give insight into features which can be trained and are thus useful for improving springboard diving performance [1].

The presented study will be carried out on the motion capture data of several kinds of dives performed by divers with national and international levels. It will give insights into how improve the synchronization between the diver and the diving board for the studied dives.

5 Conclusion

The energetic study presented in this article is a basis to better understand how optimize the synchronization between the diver and the diving board. This study is based on motion capture data of the diver and the diving board, which are modelled to compute their energies. The study of energy transfers between the diver and he diving board is a lever to better understand how improve springboard diving performance.

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