Phd Proposal
PAOLI Pole vAulting OptimaL Interaction

This Phd is founded by INRIA and will take place in MimeTic project Team

1 PROJECT DESCRIPTION

1.1 Summary

Performance in the pole vault strongly relies on the amount of energy created and on the efficiency of energy transfer throughout the running and vaulting phases. Assessing pole's mechanical properties and biomechanical actions (joint torques, muscle forces, etc) and the way they affect the athlete-structure interaction all over the vault (from the pole plant to the end of the flight phase) is of crucial interest when attempting to improve pole vault performance. This project aims to develop a coupling model of athlete-pole interaction that links human biomechanics and dynamics of slender structures driven by motion capture (marker based and IMU based) data. The model will include a 3D rigid multi-body system (human system) and a slender deformable structure model (pole model) using Cosserat-type rod theories. Both models will be driven by motion capture data. In a first step only motion capture data based on gold standard optoelectronic system will be employed to generate a reference energy flow data base. In a second step, a pole model driven by marker based optoelectronic motion capture data (to quantify the deformations in 3D) combined with a human model driven by inertial measurement units (IMU) will be used to serve as a decision support tool for coaches. The experiments will be conducted on elite pole vaulters with several pole characteristics (length, weight, rigidity). The project will allow the identification of the global responses of the coupled system and the definition of biomechanical and pole's material characteristics optimality criteria for the interaction.
The results are intended to be used in the context of the longitudinal monitoring of the pole vaulters of the French teams and the high-performance training structures.

1.2 Scientific questions

Performance in the pole vault strongly relies on the amount of energy created and on the efficiency of energy transfer throughout the running and vaulting phases. Three main factors determine the success of a vault: (1) physical abilities of the athlete (speed, strength), (2) properties of the pole (weight, length and ability to store and energy return in the most efficient way), and (3) technical (biomechanical) abilities of the athlete. In particular, the quest for optimal technique, especially at elite level, requires an accurate understanding of the complex interaction dynamics of the vaulter-pole system. Assessing pole's mechanical properties and biomechanical actions (joint torques, muscle forces, etc) and the way they affect the athlete-structure interaction all over the vault (from the pole plant to the end of the flight phase) is of crucial interest when attempting to improve pole vault performance (Linthorne, 2000).

Previous research on pole vaulting biomechanics mainly examined the pole and the vaulter in isolation. However, a coupled approach to study the pole deformations and vibrations induced by the athlete as well as the human biomechanical responses to these deformations or vibrations is crucial to accurately evaluate this athlete-material interaction. Indeed, athlete must adapt his technique using the maximum elastic properties of his equipment. This involves adapting the athlete's biomechanics to the characteristics (length, stiffness, etc.) of his equipment. The athlete's strategy therefore consists not only of transforming the kinetic energy acquired during the movement into potential energy for the structure, but also of judiciously creating efforts on the material to achieve optimal movement using the strain energy.

Previous studies were restricted to analysis of kinetic and potential energy values at discrete phases of the vault and simplified human models (Arampatzis et al., 2004; Schade et al., 2000; Schade et al., 2004; Schade et al., 2007). Such approaches limit the understanding of energy flow into and out of the pole but also resultant 3D biomechanical vaulter's adaptations requiring continuous interaction data tracking over the entire duration of the vault. Regarding the pole dynamics, most studies have been simulation based as with modelling poles. Even if finite element simulations have been considered to evaluate pole dynamics (Morlier et al., 2008; Drücker et al., 2018), such a three-dimensional theory is not convenient to be used on-field since it requires a complex partial differential equations solver and restrictive assumptions on external loads induced by the athlete in view of pole-vaulter interaction analysis. Few studies incorporated pole mechanical characteristics in terms of strain energy to understand how energy is stored and its recoil during vault in real conditions. Arampatzis et al. (2004) evaluated the pole strain energy based local efforts along the pole chord derived from the reaction force measured at the planting box. However, 2D assumptions both on pole and on human models may fail to accurately estimate energy flows over the entire vault movement. A more complete analysis of a vaulter in 3D (including deformations out of sagittal plane) is necessary for better understanding of energy flows and thus gather more insight into optimal technique. Moreover, a combination with a 3D slender continuum model driven by ecological motion capture data would be more relevant to track the dynamics of the pole and the corresponding energy flow.

Moreover, the energy transfers must be considered in relation to the effort capabilities of the athlete (Morlier and Mesnard, 2006). This leads to the identification of the instantaneous internal (joints and muscles) loads produced by the vaulter in relation to his equipment. This is possible through the musculoskeletal modelling, which has never been achieved before with 3D ecological data.

1.3 Methodological and technical ideas

This project aims to develop a model of athlete-pole interaction that links human biomechanics and dynamics of slender structures driven by motion capture (marker based and IMU based) data.

The coupling model will include a 3D rigid multi-body system (human system) and a slender deformable structure model (pole model) using Cosserat-type rod theories. Special attention will be paid to the coupling resolution to integrate solution of the deformable system within the human motion analysis solver. Both systems will be driven by motion capture data.

Regarding the pole model, the theory of Kirchhoff's rod will be considered since it describes nonlinear deformations of thin rods in which displacements may be large (finite rotations) while strains with respect to an undistorted configuration remain small. Such model corresponds to a special case of geometrically non-linear beam model (Bideau et al., 2011). Thus, a Cosserat rod model will be used so as the pole will be modeled by an arc-length parametrized curve in $\mathbb{R}^3$ describing the rod's centerline and the assignment of an orthonormal material frame to each point of the centerline. Such representation allows to calculate the bending and the twist measures in 3D at each point of the rod and consequently the bending energy and the twisting energy at each time. Kirchhoff theory of elastic rods allows the calculation of elastic energy. The price to pay will be to reconstruct the centerline positions in 3D. To do so, a motion capture based on an optoelectronic system (Qualisys system) will be used to track the positions of markers arranged regularly along the circumference of selected cross sections of the pole, enabling to determine the centroid of each section. Thus, on the assumption of circular cross-section of the pole, rod's centerline positions will be calculated from the centroids of markers located all along the periphery of each cross section.

Regarding the human model, a 3D full body biomechanical model will be used to assess joint kinematics and kinetics and derived energies of the vaulter. The model will be implemented the CusToM library (Muller et al., 2019) developed by the research team consisting of a whole-body 3D biomechanical model based on optolectronic or IMU motion capture. This numerical library can generate a personalized musculoskeletal model and can solve, from motion-capture data, inverse kinematics, external forces estimation, inverse dynamics and muscle forces estimation problems.

The methodology will include 2 main steps. The first one will use the motion capture data based on gold standard optoelectronic system (Qualisys, Sweden) for the athlete. It will enable to generate a reference energy flow data base. Since developments will serve as a decision support tool for coaches, a second step of the project will consider a pole model driven by marker based optoelectronic motion capture data (to quantify the deformations in 3D) combined with a human model driven by IMUs XSens MVN (Xsens Technologies B.V., Netherlands). The accuracy of the IMU based compared to gold-standard optoelectronic motion capture will be assessed. The experiments will be conducted on elite pole vaulters with several pole characteristics (length, weight, rigidity, etc).

Finally, the establishment of a coupling model will allow:

- the identification of the global responses of the coupled system:

- Evaluation of the energies involved and associated dissipations as well as the temporality of these energy transfers.
- Intra-system and inter-system evaluations.
- the definition of optimality criteria for the interaction:
- Optimization of material characteristics
- Optimization of human movements (motor coordination, energy transfer between body segments, etc.)
- Optimization and loadings (direction and intensity of effort) applied by the athlete.

2 REFERENCES

2.1 References related to the Phd subject

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2.2 Some References of the Team related to the subject

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3 PHD DIRECTION

3.1 Direction

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3.2 Attachment of the PhD Student

- Academic entity: Ecole Normale Supérieure de Rennes

- Laboratory : Centre Inria de l’université de Rennes and IRISA (MimeTic Team)
- Doctoral school: MATISSE

3.3 Positioning and scientific environment

The organization of INRIA MimeTIC team around IRISA/INRIA scientists and M2S scientists has led to numerous collaborations between including PhD Thesis and postdoctoral co-supervisions through national and international projects.

This Phd thesis (PAOLI project) is part of the perspective of monitoring very high-level pole vaulters in the perspective of international events (Olympic games & world championships). In this regard, the project is in line with the expectations of the scientific staffs of French federation responsible for performance support. The scientific developments within the PAOLI project thus may bring innovative training programs and consistent use of in situ data for performance improvement.
INSEP partner will be implied in accordance with INRIA (collaboration in the perspective of 2024 Olympic and Paralympic games) and the French to Athletics federation.
The experimental platform IMMERMOVE will be used in this project for the calibration and validation of the algorithms. It has been partially financed within the framework of the last State-Region Plan Contract for Brittany. It is carried within the framework of the Immerstar project by the ENS Rennes, the University of Rennes 2, the University of Rennes, the INSA Rennes and the INRIA Bretagne/Atlantique research center, all of which are also associated with the IRISA UMR 6074 laboratory, of which the MimeTIC team is one, and also carried by the M2S (EA7470). Immerstar is supported by French government funding managed by the National Research Agency under the Investments for the Future program (PIA) with the grant ANR-21-ESRE-0030 (CONTINUUM project).