Université Grenoble Alpes

Rapport d'évaluation du mémoire de thèse / Evaluation report of the PhD thesis

Doctorant PhD student
Nom prénom / Full name: PAGNON David
Ecole Doctorale / Doctoral School: Mathématiques, Sciences et technologies de l'Information, Informatique
Titre thèse / PhD Title: Design and evaluation of a biomechanically consistent method for markerless kinematic analysis of sports motion

Rapporteur Reviewer
Nom prénom / Full name: KULPA Richard
Etablissement / Institution: Université Rennes 2
Statut, fonction / Status, position: Professeur des Universités

Qualité du mémoire : structuration, rédaction & illustrations / Thesis quality, style & illustrations
(A titre indicatif/For information : Exceptionnel = top 5%, Très bon/very good = top 25 %)

⇨ Insatisfaisant / Unsatisfactory [ ] Satisfaisant / Satisfactory [ ] Bon / Good [ ]
Très bon / Very good [ ] Exceptionnel [X]

Commentaires/comments :
David Pagnon's PhD thesis is well written, well structured, pedagogically explained with the addition of diagrams and tables to synthesize the results but also appendices to bring more information.

Contexte/ collaborations, background : état de l'art / state of the art :

⇨ Insatisfaisant / Unsatisfactory [ ] Satisfaisant / Satisfactory [ ] Bon / Good [ ]
Très bon / Very good [X] Exceptionnel [ ]

Commentaires/comments :
The state of the art is split in two parts, first to detail the capture technologies used for sports movement analysis and highlights the need for a markerless solution for high-level use. Once this context is established, the second state of the art chapter details video-based sports motion analysis. This division is not classic but is particularly efficient.

Qualité scientifique : méthodologie, expérimentations, validation
Scientific quality, methodology, experiments, validation

⇨ Insatisfaisant / Unsatisfactory [ ] Satisfaisant / Satisfactory [ ] Bon / Good [ ]
Très bon / Very good [X] Exceptionnel [ ]

Commentaires/comments :
David Pagnon produced during his thesis a consequent work with a clear guideline about the objective of this PhD. He proposed innovative methodologies as well as experimental studies to assess their robustness and accuracy. The number of publications illustrates this statement: two articles in Sensor (part 1 and 2), an article in the Journal of Open Source Software, a poster in the ECSS conference, a presentation at the 17th International Symposium on 3-D Analysis of Human Movement and one at the Rencontres scientifiques de la

haute performance en cyclisme 2022. David Pagnon has also published a narrative review alongside the thesis as first author.

Apports personnels : originalité, valorisation, perspectives
Personal contributions : originality, exploitation and application of results, prospects.

Insatisfaisant / Unsatisfactory [ ] Satisfaisant / Satisfactory [ ] Bon / Good [ ]
Très bon / Very good [ ] Exceptionnel [X]

Commentaires/comments :

David Pagnon produced during his thesis an open source software solution that can be used by the community. I want to emphasize this point because making code available requires additional work in terms of clean and readable programming, documentation and answering questions and problems encountered by people who use it.

Conclusions du rapporteur / Reviewer's conclusions
Commentaires/comments :
Considering the quality of the work and of the manuscript, I give a very favorable opinion to the PhD defense of Mr. David Pagnon in order to obtain the title of Doctor of the University Grenoble Alpes. The combined work on scientific methodologies and the development of open source software solution is definitely a strong point to take into account.

Avis du rapporteur / Reviewer's opinion :
Défavorable à la soutenance / Unfavorable to the defence [ ] Favorable [X]

Date 10/02/2023 Signature

Visa du directeur de l'école doctorale :

Rapport détaillé, commentaires libres, questionnements
Detailed report, free comments, questions
Cf. document joint.

UNIVERSITÉ RENNES 2
RENNES 2

UNIVERSITÉ RENNES 2
SKOL-VEUR ROAZHON 2
CAMPUS VILLEJEAN
Place du recteur
Henri Le Moal CS 24307
35043 Rennes cedex
France
T +33 (0)2 99 14 10 00
www.univ-rennes2.fr

Richard KULPA
UFR STAPS
Université Rennes 2
25 avenue Charles et Raymonde Tillon
35000 Rennes

Object
Report on David Pagnon's PhD thesis

Rennes, Feb. 09 2023

David Pagnon's PhD thesis focuses on motion capture in the specific context of performance analysis for high-level sports. The complex systems used in the laboratory are not able to meet the requirements and constraints of this sport context. The thesis therefore focuses on the creation of methods for robust, accurate, and versatile markerless motion capture that can be easily used by athletes and coaches. To this end, a software solution is proposed to bridge the gap between computer vision methods and biomechanical gesture simulation.

The PhD is divided into seven main chapters followed by a general conclusion. The structure may seem unusual with a state of the art that is only 12 pages long, but in reality it is split into two parts as indicated in a general description of the structure of the thesis. This first part of the state of the art details the capture technologies used for sports movement analysis and highlights the need for a markerless solution for high-level use. Once this context is established, a second 38-page state of the art chapter details video-based sports motion analysis. It is followed by chapters 3, 4 and 5 which are the core contributions of this thesis with the implementation that has been made to meet the objective of the thesis, as well as the robustness and accuracy assessments of this methodology. Finally, chapters 6 and 7 describe two applications of this solution in the context of sports performance analysis in boxing with only Go-Pro cameras and in BMX with the simultaneous acquisition of the rider and bike.

The first chapter contains a first state of the art explaining the different existing motion capture systems, their strengths but also their weaknesses in order to highlight the fact that there is a lack of a motion capture solution for kinematic gesture analysis that can be used in the highly constrained context of high-level sport while providing robust and accurate data. The final section of this chapter is a synthesis that describes the objective of this thesis: to propose a markerless motion capture solution that bridges the gap between OpenPose software which allows estimating 2D poses from camera images and OpenSim one which simulates a biomechanical model of a human from 3D motion data. This software solution is released as open source for the benefit of the community.

The second chapter then describes the different steps and methodologies needed to implement a kinematic analysis of gesture from video. This chapter follows a fairly

CAMPUS LA HARPE
Avenue Charles Tillon
CS 24414
35044 Rennes cedex

CAMPUS MAZIER
2, Avenue Antoine Mazier
22015 St-Brieuc cedex 1

UNIVERSITÉ RENNES 2
SKOL-VEUR ROAZHON 2
CAMPUS VILLEJEAN
Place du recteur
Henri Le Moal CS 24307
35043 Rennes cedex
France
T +33 (0)2 99 14 10 00
www.univ-rennes2.fr

logical order: how to estimate 2D poses from camera images, how to calibrate cameras to obtain their intrinsic and extrinsic properties and how to deduce 3D poses from 2D camera poses by triangulation. Finally, it describes the impact of the biomechanical skeleton modelling used by the scaling and inverse kinematics solutions in order to find the orientations of the segments. This order of description of the methodologies faces the difficulty that some calibration methodologies rely for example on the projection of 3D camera data, seen later, but this does not hinder the reading of the chapter. In the end, this chapter is very pedagogical, very well written and comprehensive. Having a clearer description of the contributions of this thesis throughout each major section of this chapter would have been an additional asset to properly situate the contributions made.

The third chapter describes the core of the thesis, the Pose2Sim software which was developed and released during the PhD. It is written in Python and is made available to the community via an open source repository on GitHub. A diagram allows to situate this contribution in relation to the OpenPose and OpenSim software on which it relies to propose a complete chain from video capture to the simulation of sports movement. It should be noted that the following contribution chapters also begin with a useful overview diagram. Pose2Sim aims at linking OpenPose which allows to find 2D poses from video images and OpenSim which allows to simulate biomechanical models by proposing a triangulation of 2D data in order to obtain 3D data and then to provide these data (and to adapt the biomechanical model used) in OpenSim in order to exploit its methods of scaling and inverse kinematics to find the joint centers as well as the orientations of segments.

This chapter describes the different functionalities implemented in Pose2Sim and allows to understand the articulation of the contributions and the reason of the choices made. These contributions concern the calibration of the cameras (intrinsic factors which remain constant for each camera and extrinsic factors which depend on the placement of these cameras during the experiments). The existing triangulation methods as well as the solution proposed in Pose2Sim are also presented, followed by the transformation of the 3D pose estimation to the 3D joint kinematics. It would have been interesting at some points to have more details on some of the parameter choices made, such as the impact of optimizing the weights of the Weighted DLT to triangulate 2D poses from OpenPose, or how they consider the labelling errors and joint center calculation errors via the GUI that has been developed, or finally on the weighting coefficients applied to the joints for scaling. Some of this information is described in more detail in the following chapters. This is due to the relevant choice of having chapters associated with published articles. This chapter is adapted from the article published in the Journal of Open Source Software: "Pose2Sim: An Open-source Python Package for multiview markerless kinematics".

The fourth chapter focuses on the validation of the robustness of Pose2Sim. To this end, video streams of walking, running and cycling movements were created from virtual cameras placed in a 3D graphical environment. This environment was generated in the studio from the video capture of one subject on a green background from which the participant's mesh was reconstructed. This idea is very interesting as it allows the videos used to be standardized and therefore modified in a controlled manner. This methodology is however very complex to implement and hopefully relies on the Kinovis capture platform. The result is realistic and the logical questioning about the impact of this realism on the results is well argued.

In order to evaluate the robustness of Pose2Sim, the generated images were then altered according to 4 conditions: Reference Condition with unaltered images, Poor Image Quality with blurrier and darker image, Less Cameras with only 4 cameras instead of 8 and

CAMPUS LA HARPE
Avenue Charles Tillon
CS 24414
35044 Rennes cedex

CAMPUS MAZIER
2, Avenue Antoine Mazier
22015 St-Brieuc cedex 1

UNIVERSITÉ RENNES 2
UNIVERSITÉ RENNES 2
SKOL-VEUR ROAZHON 2
CAMPUS VILLEJEAN
Place du recteur
Henri Le Moal CS 24307
35043 Rennes cedex
France
T +33 (0)2 99 14 10 00
www.univ-rennes2.fr

Calibration Errors in which the calibration error is set to 1cm. The results are described for each step of the Pose2Sim pipeline and show that despite degraded image conditions the results remain globally satisfactory. Larger errors are obtained with a cycling movement for example when only 4 cameras are used. These different evaluations also allow a better understanding of the limits of this methodology. This chapter is adapted from the article published in Sensors: "Pose2Sim: An End-to-End Workflow for 3D Markerless Sports Kinematics—Part 1: Robustness".

Chapter 5 presents the evaluation of the accuracy of Pose2Sim. The movements of the same subject are again captured in the studio but this time the subject is equipped with reflective markers in order to perform a double marker-based and markerless motion capture. The comparison of the two approaches allows to estimate the error produced by the markerless system compared to the marker-based one, keeping in mind that the conditions remain different in terms of resolution and camera frequency for example. The results again show globally interesting results with again more significant errors, for example in cycling due to occlusions and on some joints such as the hips where an offset persists despite the use of a different body model which frees up degrees of freedom in the spine to try and limit this offset. This study focuses on the lower body but the upper body results are given in the appendix. The errors are larger in the upper body. This could be explained by a too simple upper body model and an insufficient number of markers for joints as complex as the shoulder. This chapter is adapted from the article published in Sensors: "Pose2Sim: An End-to-End Workflow for 3D Markerless Sports Kinematics—Part 2: Accuracy".

Chapter 6 presents an exploitation of Pose2Sim to carry out the capture of isolated movements of 3 boxers directly on the training site of the French Training Centre. The objective is to evaluate the ability of the system to extract the KPI of a jab, a high hook and a low hook, using simple GoPro cameras. To evaluate the motion capture, a Qualisys optoelectronic motion capture system is also installed and the subject is equipped with reflective markers.

This experimentation in real conditions also makes it possible to highlight the contribution of the camera calibration in order to obtain their extrinsic parameters (the intrinsic parameters being calculated by OpenCV and a checkerboard). But above all, contrary to previous studies, the GoPro cameras are not synchronised. A post-synchronisation phase is performed on the peaks of the 2D keypoints speeds and it would be interesting to evaluate other methodologies, especially since the results show the absence of these peaks on some gestures and that a non-perfect synchronisation of the GoPro cameras has been obtained. The results also show again that some of the calibration errors are compensated by the model during the inverse kinematics simulation. At the end, this example shows the ability of the solution to provide a good compromise between accuracy of capture and the fact that the system does not require any particular equipment on the subject. This chapter is a detailed version of the poster presented at the congress of the European College of Sport Science (ECSS): "A 3D markerless protocol with action cameras – Key performance indicators in boxing".

Finally, chapter 7 is a complementary part to the rest of the thesis as it proposes a preliminary study to evaluate the coupling of the motion capture of a BMX rider with that of a piece of equipment, in this case his bike, during the race start. For this study, a Qualisys capture system of only 6 Miqus cameras is used. The main contribution of this chapter is the management of the interaction between the capture of the bike's motion with the DeepLabCut software and that of the cyclist. Indeed the pilot and the bike form a kinematic chain which is closed on hands and feet. However, the relationship between

CAMPUS LA HARPE
Avenue Charles Tillon
CS 24414
35044 Rennes cedex

CAMPUS MAZIER
2, Avenue Antoine Mazier
22015 St-Brieuc cedex 1

UNIVERSITÉ RENNES 2
RENNES 2

UNIVERSITÉ RENNES 2
SKOL-VEUR ROAZHON 2
CAMPUS VILLEJEAN
Place du recteur
Henri Le Moal CS 24307
35043 Rennes cedex
France
T +33 (0)2 99 14 10 00
www.univ-rennes2.fr

the hands and the handlebars for example is not perfect and rotations around the handlebar may exist. A model based on the duplication of hands and feet on the kinematic chains of the bicycle and the pilot is therefore proposed. It allows to apply weld constraints only between these two entities. However, the results show that the inverse kinematics do not converge when these constraints are activated and further studies are needed, especially with better capture conditions. This chapter was presented at the "Rencontres scientifiques de la haute performance en cyclisme".

The general conclusion summarizes all the contributions and their limitations before proposing some perspectives to this work.

David Pagnon's PhD thesis is well written, well structured, pedagogically explained with the addition of diagrams and tables to synthesize the results but also appendices to bring more information. He produced during his thesis a consequent work with a clear guideline and with a will to produce an open source software solution that can be used by the community. I want to emphasize this point because making code available requires additional work in terms of clean and readable programming, documentation and answering questions and problems encountered by people who use it. This aspect of the thesis coupled with the fact that he also conducted experiments to validate his approach makes his work interesting. The number of publications speaks for itself: two articles in Sensor (part 1 and 2), an article in the Journal of Open Source Software, a poster in the ECSS conference, a presentation at the 17th International Symposium on 3-D Analysis of Human Movement and one at the Rencontres scientifiques de la haute performance en cyclisme 2022. David Pagnon has also published a narrative review alongside the thesis as first author.

Considering the quality of the work and of the manuscript, I give a very favorable opinion to the PhD defense of Mr. David Pagnon in order to obtain the title of Doctor of the University Grenoble Alpes.

Prof. Richard KULPA

CAMPUS LA HARPE
Avenue Charles Tillon
CS 24414
35044 Rennes cedex

CAMPUS MAZIER
2, Avenue Antoine Mazier
22015 St-Brieuc cedex 1