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dans **l'École Doctorale l'École Doctorale Mathématiques, Sciences et technologies de l'Information, Informatique**

"Design, evaluation, and application of a workflow for biomechanically consistent markerless kinematics in sports"

"Conception, évaluation, et application d'une méthode biomécaniquement cohérente de cinématique sans marqueurs en sport"

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Remerciements

*R*emerciements possibles ici.

Abstract

*A*bstract.

Résumé

*R*ésumé.

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Introduction générale

*I*ntroduction générale.

1

State of the art

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Résumé du chapitre possible ici.

This chapter is an up-to-date version of the introduction of the previously published paper "Pose2Sim : An End-to-End Workflow for 3D Markerless Sports Kinematics—Part 1 : Robustness" [[Pagnon2021](#)]

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1.1 Overall context of kinematics in sports

Kinematic analysis in sports is a difficult challenge which highlights the limits of classic marker-based methods [Mündermann2006]. Reflective marker-based camera systems are complex to set up, require specific lightning conditions, and are overall challenging to use out of a lab. Markers may fall off the body due to sharp accelerations or sweat, as well as hinder the natural movement of athletes, which is likely to affect their warm-up and focus. While the accuracy of landmark location is claimed to be sub-millimetric in marker-based methods [Topley2020], marker placement is tedious, intrusive, prone to positioning variability from the operator [Tsushima2003], and subject to skin movement artifacts, especially on soft tissues. Della Croce et al. found out that inter-operator variations in marker placements range from 13 to 25 mm, which can propagate up to 10° in joint angle prediction [Gorton2009, della Croce1999]. Tissue artifacts account for up to a 2.5 cm marker displacement at the thigh for example, which can cause as much as a 3° error in knee joint angles tissues [Benoit2015, Cappozzo1995]. Joint positions must be calculated explicitly in marker-based methods, which introduces more variability : these errors range up to 5 cm, which can contribute up to 3° of error in lower limb joint kinematics [Leboeuf2019]. Nevertheless, since marker-based methods benefit from decades of research, they are still considered as the reference method for motion capture.

Consequently, other approaches based on alternative technologies have been investigated over the past years. For example, wearable Inertial Measurement Units (IMUs) offer the advantage of getting away from all camera-related issues such as field of view, occlusions, and controlled environment [Zhang2013]. They still have the disadvantage of being an external equipment to still wear, involving high technical skills, and being sensitive to ferromagnetic disturbances and exposed to drift over time [Ahmad2013]. Another approach involves depth-field cameras (RGBD), which give access to a 2.5D world (only the depth of the front facing plane of view is measured), or even to full 3D with a network of few RGBD cameras [Carraro2017, Choppin2013, Colom-bel2020]. On the other hand, these cameras suffer from a sensitivity to lightning conditions, they work at lower framerates, and they are short-range [Han2013].

A recent breakthrough has come from Computer Vision. The explosion of deep-learning based methods from 2D camera videos, for which the research has skyrocketed around 2016 [Wang2021b], is related to the increase in storage capacities and huge improvements in GPU computing. A search on ScienceDirect for “deep learning 3D human pose estimation” produced fewer than 100 papers per year until 2015, and the number is now reaching almost 750 over the span of 5 years, fitting an exponential curve (Figure 1.1).

It has rekindled interest from the Biomechanics community towards image-based kinematics, which is where it all started with the invention of chronophotograph in the 19th century by Marey in France, and Muybridge in the USA [Baker2007]. Currently, two approaches coexist in human and animal motion analysis for pose estimation : on the one hand, computer vision using deep-learning techniques mostly focus on joint positions only ; while the interest of biomechanics lies in kinematics, that involves joint angles. One of the main challenges is to bridge the gap between these two worlds, and to take advantage of deep-learning technologies for kinematic analysis [Cronin2021, Seethapathi2019].

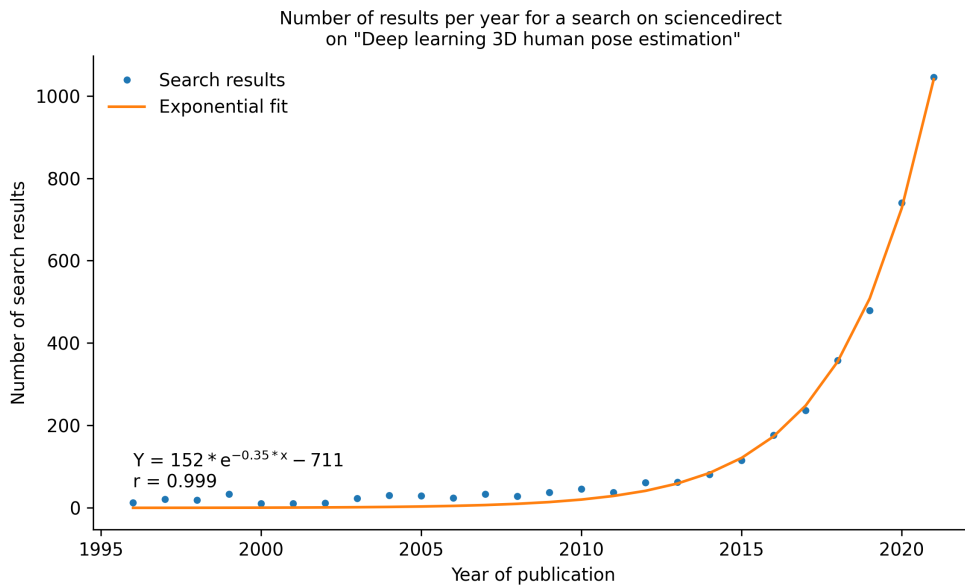


FIGURE 1.1 – The search for “deep learning 3D human pose estimation” (dots) fits an exponential curve (line). The search produced less than 100 results until 2015. Over the course of 5 years, the number has reached almost 750 of them, and is now well over a 1000 per year.

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1.2 2 dimensional analysis

1.2.1 2D pose estimation

The most well-known off-the-shelf 2D human pose estimation solutions are OpenPose [Cao2019], and to a lesser extent AlphaPose [Fang2017]. While both show similar results, OpenPose has the advantage of being a bottom-up approach, whose computation time does not increase with the number of persons detected [Cao2019]. A bottom-up approach first detects all available joint keypoints, and then associates them to the right persons; while a top-bottom approach first detects bounding boxes around each person, and then finds joint keypoints inside of them. OpenPose has been trained on the CMU Panoptic Dataset [Joo2015], with 511 synchronized videos of multiple people in motion, alone or engaged in social activities. Another 2D pose estimation toolbox is DeepLabCut [Mathis2018], which was initially intended for markerless animal pose estimation, but which can be custom trained for the detection of any human or not human keypoint with a relatively small dataset. All of these tools are open-source. Other approaches have shown even better results on evaluation datasets (see review [Chen2020]), but they are generally slower and not as widespread.

1.2.2 2D kinematics from 2D pose estimation

Some authors bridge 2D pose estimation to more biomechanically inspired goals, such as gait kinematics analysis. Kidzinski et al. present a toolbox for quantifying gait pathology that runs in a Google Colab [Kidziński2020]. Stenum et al. evaluate gait kinematics calculated from OpenPose input concurrently with a marker-based method. Mean absolute error of hip, knee and ankle sagittal angles were 4.0°, 5.6° and 7.4° [Stenum2021]. Liao et al. have not released their code, but they use OpenPose outputs to train a model invariant to view [Liao2020]. Viswakumar et al. perform direct calculation of the knee angle from an average phone camera processed by OpenPose [Viswakumar2019]. They show that OpenPose is robust to challenging clothing such as large Indian pants, as well as to extreme lightning conditions. Other sports activities have been investigated, such as lower body kinematics of vertical jump [Drazan2021] or underwater running [Cronin2019]. Both

works train their own model with DeepLabCut. Serrancoli et al. fuse OpenPose and force sensors to retrieve joint dynamics in a pedaling task [Serrancoli2020].

1.3 3 dimensional analysis

1.3.1 3D pose estimation

There are a lot of different approaches for markerless 3D human pose estimation and listing them all is beyond our scope (see review [Wang2021b]). Some more ancient ones are not based on deep-learning and require specific lightning and background conditions, such as visual-hull reconstruction [Ceseracciu2014]. Some directly lift 3D from a single 2D camera (see review [Chen2020]), with different purposes : one estimates the positions of a set of keypoints around the joint instead of determining only the joint center keypoint, so that axial rotation along the limb is solved [Fisch2020]; SMPL and its sequels retrieve not only joint positions and orientations, but also body shape parameters [Loper2015]; while XNect primarily focuses on real time [Mehta2020]. A few approaches even strive to estimate 3D dynamics and contact forces from a 2D video input [Rempe2021, Li2019]. Rempe et al. solve occlusions from a 2D input [Rempe2020], but this remains a probabilistic guess that may be unsuccessful in case of unconventional positions of hidden limbs, whereas using more cameras would have given more trustworthy results. Haralabidis et al. fuse OpenPose results from a single monocular video and two IMU outputs, and solve kinematics of the upper body in OpenSim (an open-source biomechanical 3D analysis software [Delp2007, Seth2018]) in order to examine the effects of fatigue on boxing [Haralabidis2020].

Some research attempts to solve 3D pose estimation from a network of uncalibrated cameras, i.e., cameras whose extrinsic parameters (translation and rotation with respect to the coordinate system), intrinsic parameters (focal length, pixel size, etc.), and distortion coefficients are not known. It either uses 2D pose estimations of each view as visual cues to calibrate on [Takahashi2018], or an adversarial network that predicts views of other cameras, compares them to real views, and adjusts its calibration accordingly [Ershadi-Nasab2021]. Dong et al. recover 3D human motion from unsynchronized and uncalibrated videos of a repeatable movement found on internet videos (such as a tennis serve performed by a celebrity) [Dong2020]. Using uncalibrated videos is still a very experimental trend, that would require more research before being used in biomechanics.

We choose to focus on the methods that estimate 3D pose by triangulating 2D pose estimations from a network of multiple calibrated cameras. The classical evaluation metric is the MPJPE (Mean Per Joint Position Error), which is the average Euclidian distance between the estimated and the ground truth joint coordinate. Most methods take OpenPose as an input for triangulation, and more specifically the body_25 model. Labuguen et al. evaluate 3D joint positions of a pop dancer with a simple Direct Linear Transform triangulation (DLT [Hartley1997, Miller1980]) from 4 cameras [Labuguen2020]. Apart from the upper body for which error goes up to almost 700 mm, the average joint position error is about 100 mm. Nakano et al. examine three motor tasks (walking, countermovement jumping, and ball throwing), captured with 5 cameras and triangulated with the same methods, with a subsequent Butterworth filter [Nakano2019]. 47% of the errors are under 20 mm, 80% under 30 mm, and 10% are above 40 mm. The largest errors are mostly caused by OpenPose wrongly tracking a joint, for example by swapping the left and the right limb, what causes large errors up to 700 mm. This may be fixed either by using a better 2D pose estimator, or by using more cameras to reduce the impact of an error on a camera, or else by considering the temporal continuity in movement.

Slembrouck et al. go a step further and tackle the issue of limb swapping and of multiple persons detection [Slembrouck2020]. In case of multiple persons detection, one needs to make sure

they triangulate the person detected on one camera to the same person detected on the other ones. Slembrouck et al. manage to associate persons across cameras by examining all the available triangulations for the neck and mid-hip joints : the persons are the same when the distance between the triangulated point and the line defined by the detected point and the camera center is below a certain threshold. They only focus on lower limb. Their first trial features a person running while being filmed by seven cameras, whereas their second one involves a person doing stationary movements such as squats while filmed by 3 cameras. After filtering, the average positional error in the first case is about 40 mm, and it is roughly 30 mm in the second case (less than 20 mm for the ankle joint). Other authors deal with the multiperson issue in a slightly different way [Bridge-man2019, Chu2021, Dong2019]. In average, if the detected persons are correctly associated and the limbs don't swap, the average joint position error for an OpenPose triangulation is mostly below 40 mm.

Some triangulation methods not based on OpenPose reach even better results on benchmarks, although it comes at the cost of either requiring heavy computations, or of being out of reach for non-expert in computer vision. The classic approach is to detect probability maps for each joint, to assume that the maximum probability is the actual 2D joint position, and then to triangulating these scalar positions. Instead of this, the main two state-of-the art methods directly perform a volumetric triangulation of the heatmaps, and only then take the maximum probability. By working this way, they keep all the information available for as possible for as long as possible. They manage to lower their MPJPE to about 20 mm [He2020, Iskakov2019].

1.3.2 3D kinematics from 3D pose estimation

Instead of just working on 3D joint positions, the issue of 3D markerless kinematics (i.e., gait parameters and joint angles) is starting to be tackled. Zago et al. evaluate gait parameters computed by triangulating 2 videos processed by OpenPose, and notice that straight gait direction, longer distance from subject to camera, and higher resolution make a big difference in accuracy [Zago2020]. D'Antonio et al. perform a simple triangulation of the OpenPose output of two cameras, and compute direct Euler angle calculations for the lower limb [D'Antonio2021]. They compare their results to IMU and point out that errors are higher for running than for walking, and are also rather inconsistent : up to 14°, although they can get down to 2 to 7° if the two cameras are set laterally rather than in the back of the subject. Theia3D, a recent commercial (and not open) solution, estimates the positions of a set of keypoints around the joint, and then uses a multi-body optimization approach to solve inverse kinematics [Kanko2021a, Kanko2021b]. They notice an offset in hip and ankle angles between their markerless system and the reference marker-based one, likely due to different skeletal models. Once this offset is removed the root mean square error (RMSE) in lower limb roughly ranges between 2 and 8° for flexion/extension and abduction/adduction angles, and up to 11.6° for internal/external rotation. AniPose broadens the perspective to the kinematics of any human or animal with a DeepLabCut input, instead of OpenPose. They offer custom temporal filters, as well as spatial constraints on limb lengths [Karashchuk2021].

1.4 Statement of need

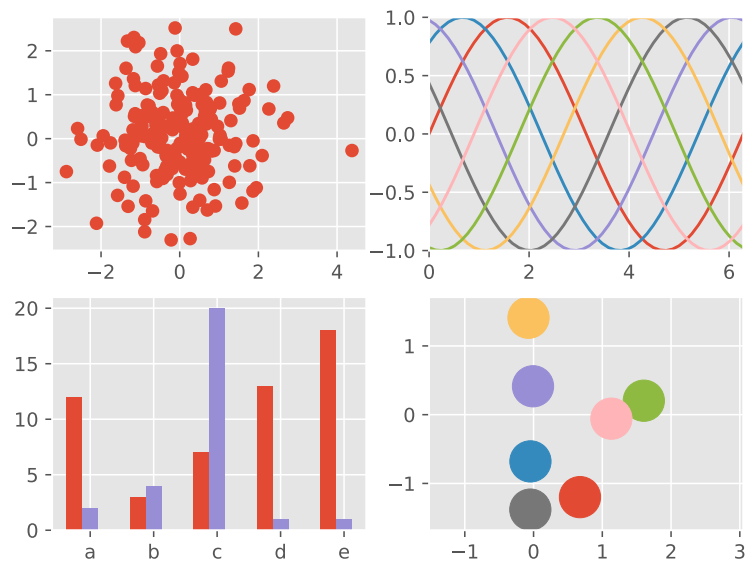
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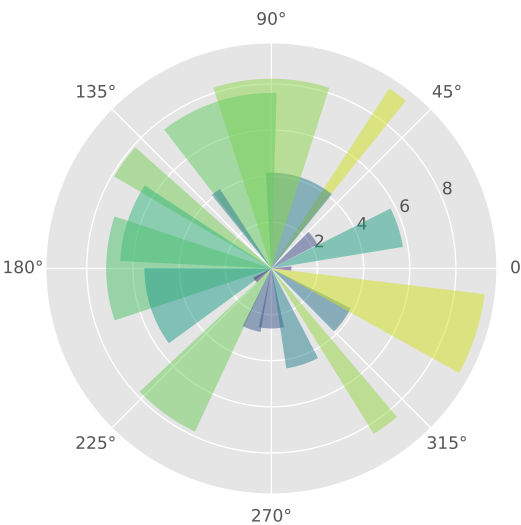
1.5 Exemples

1.5.1 Figures

La Figure 1.2 est un exemple d'intégration d'une figure multiple.
Il est bien entendu possible de faire référence à la Figure 1.2a ou à la Figure 1.2b.



(a) Exemple subplot



(b) Exemple diagramme polaire

FIGURE 1.2 – Exemple de Figures multiple

1.5.2 Tableaux

Générateur en ligne [ici](#).

Un exemple de tableau générée par cet outil est présenté Table 1.1.

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β		1	2
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TABLEAU 1.1 – *Exemple de tableau*

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1.6 Section 2

1.6.1 Sous-section 1

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2

Theoretical framework

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2.1 Machine learning

2.1.1 Principles and history

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2.1.2 Application to object detection and localization

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2.1.3 Pose detection : Different architectures, different models, different datasets

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2.2 3D reconstruction

2.2.1 Pinhole camera model

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2.2.2 Calibration

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2.2.3 Triangulation

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3

Proposed solution : Pose2Sim python package

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Résumé du chapitre possible ici.

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3.1 Introduction to the workflow

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3.2 2D pose detection

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3.3 Pose2Sim core

3.3.1 Tracking of the person viewed by the most cameras

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3.3.2 Triangulating by weighted direct linear transform

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3.3.3 Filtering

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3.4 Pose2Sim skeletal model

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3.5 Limitations and perspectives

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3.6 Helper functions and vizualisation tools

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4

Pose2Sim robustness

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Résumé du chapitre possible ici.

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4.1 Introduction

4.1.1 Robustness definition

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4.1.2 Assessing robustness

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4.2 Methods

4.2.1 Experimental setup

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4.2.2 Participant and protocol

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4.2.3 Challenging robustness

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4.2.4 Statistical analysis

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4.3 Results

4.3.1 Data collection and 2D pose estimation

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4.3.2 Pose2Sim tracking, triangulation, and filtering

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4.3.3 Relevance, repeatability and robustness of angles Results

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4.4 Discussion

4.4.1 Pose2Sim

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4.4.2 Relevance, repeatability and robustness

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4.4.3 Limits and perspectives

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5

Pose2Sim accuracy

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5.1 Introduction

5.1.1 State of the art

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5.1.2 Assessing accuracy

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5.2 Methods

5.2.1 Data collection

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5.2.2 Markerless analysis

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5.2.3 Marker-based analysis

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5.2.4 Statistical analysis

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5.3 Results

5.3.1 Concurrent validation

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5.3.2 Comparison with other systems

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5.4 Discussion

5.4.1 Strengths of Pose2Sim and of markerless kinematic

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5.4.2 Limits and perspectives

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5.5 Conclusions

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6

Pose2Sim in suboptimal conditions : Application to boxing

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Résumé du chapitre possible ici.

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6.1 Objectives

6.1.1 Key Performance Indicators in boxing

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6.1.2 Limits of research-grade systems in competitions

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6.1.3 Objectives

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6.2 Methods

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6.2.2 Pose-calibration on ring dimensions

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6.2.3 Post-synchronization on 2D movement speeds

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6.2.4 GoPro spatio-temporal base into Qualysis'

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6.2.5 Statistical analysis

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6.3 Results

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6.4 Discussion

6.4.1 Equipment and protocol vs. pose estimation model

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6.4.2 Pros and cons of different systems

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7

OpenPose and DeepLabCut together with Pose2Sim : Application to BMX racing

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Résumé du chapitre possible ici.

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7.1 Introduction

7.1.1 The start in BMX racing

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7.2 Methods

7.2.1 Material and protocol

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7.2.2 Pilot inverse kinematics

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7.2.3 Bike inverse kinematics

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7.2.4 Joined pilot and bike inverse kinematics

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7.3 Results

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7.4 Discussion

7.4.1 On these data

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7.4.2 Limits and perspectives

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Conclusion générale

Conclusion ici.

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Annexe 1 : Titre

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A.1 Section 1

A.1.1 Sous section 1

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B

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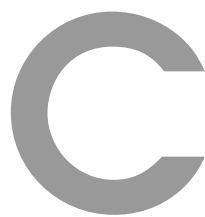
B.1 Section 1

B.1.1 Sous section 1

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Annexe 3 : Titre

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C.1 Section 1

C.1.1 Sous section 1

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"Design, evaluation, and application of a workflow for biomechanically consistent markerless kinematics in sports"

"Conception, évaluation, et application d'une méthode biomécaniquement cohérente de cinématique sans marqueurs en sport"

Résumé

Ici ... résumé en français.

Mots-clés : Mots clés

Abstract

Ici ... résumé en anglais.

Keywords : markerless motion capture ; sports performance analysis ; kinematics ; computer vision ; openpose ; opensim ; python package

