RESEARCH CENTRE

Inria Centre at Rennes University

IN PARTNERSHIP WITH:

Université Rennes 2, École normale supérieure de Rennes, Université de Rennes

2024
ACTIVITY REPORT

Project-Team

MIMETIC

Analysis-Synthesis Approach for Virtual Human Simulation

IN COLLABORATION WITH: Institut de recherche en informatique et systèmes aléatoires (IRISA), Mouvement, Sport, Santé (M2S)

DOMAIN

Perception, Cognition and Interaction

THEME

Interaction and visualization

Inria

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Project-Team MIMETIC

Creation of the Project-Team: 2014 January 01

Keywords

Computer sciences and digital sciences

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A5.1.5. – Body-based interfaces

A5.1.9. – User and perceptual studies

A5.4.2. – Activity recognition

A5.4.5. – Object tracking and motion analysis

A5.4.8. – Motion capture

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A5.6. – Virtual reality, augmented reality

A5.6.1. – Virtual reality

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A5.10.3. – Planning

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Other research topics and application domains

B1.2.2. – Cognitive science

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B2.8. – Sports, performance, motor skills

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B9.2.2. – Cinema, Television

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B9.4. – Sports

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2 Overall objectives

2.1 Presentation

MimeTIC is a multidisciplinary team whose aim is to better understand and model human activity in order to simulate realistic autonomous virtual humans: realistic behaviors, realistic motions and realistic interactions with other characters and users. It leads to modeling the complexity of a human body, as well as of his environment where he can pick up information and where he can act on it. A specific focus is dedicated to human physical activity and sports as it raises the highest constraints and complexity when addressing these problems. Thus, MimeTIC is composed of experts in computer science whose research interests are computer animation, behavioral simulation, motion simulation, crowds and interaction between real and virtual humans. MimeTIC also includes experts in sports science, motion analysis, motion sensing, biomechanics and motion control. Hence, the scientific foundations of MimeTIC are motion sciences (biomechanics, motion control, perception-action coupling, motion analysis), computational geometry (modeling of the 3D environment, motion planning, path planning) and design of protocols in immersive environments (use of virtual reality facilities to analyze human activity).

Thanks to these skills, we wish to reach the following objectives: to make virtual humans behave, move and interact in a natural manner in order to increase immersion and improve knowledge on human motion control. In real situations (see Figure 1), people have to deal with their physiological, biomechanical and neurophysiological capabilities in order to reach a complex goal. Hence MimeTIC addresses the problem of modeling the anatomical, biomechanical and physiological properties of human beings. Moreover these characters have to deal with their environment. First, they have to perceive this environment and pick up relevant information. Thus, MimeTIC focuses on the problem of modeling the environment including its geometry and associated semantic information. Second, they have to act on this environment to reach their goals. It leads to cognitive processes, motion planning, joint coordination and force production in order to act on this environment.

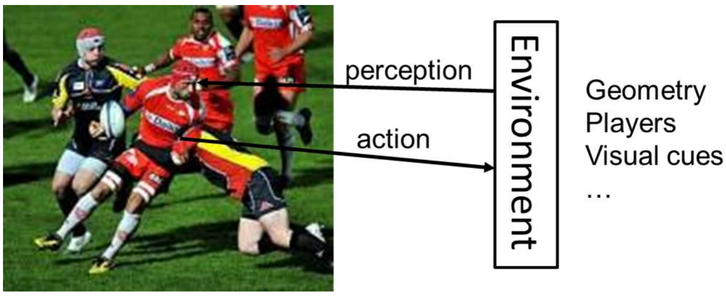

Figure 1: Main objective of MimeTIC: to better understand human activity in order to improve virtual human simulations. It involves modeling the complexity of human bodies, as well as of environments where to pick up information and act upon.

In order to reach the above objectives, MimeTIC has to address three main challenges:

- deal with the intrinsic complexity of human beings, especially when addressing the problem of interactions between people for which it is impossible to predict and model all the possible states of the system,
- make the different components of human activity control (such as the biomechanical and physical, the reactive, cognitive, rational and social layers) interact while each of them is modeled with completely different states and time sampling,
- and measure human activity while balancing between ecological and controllable protocols, and to be able to extract relevant information in wide databases of information.

As opposed to many classical approaches in computer simulation, which mostly propose simulation without trying to understand how real people act, the team promotes a coupling between human activity analysis and synthesis, as shown in Figure 2.

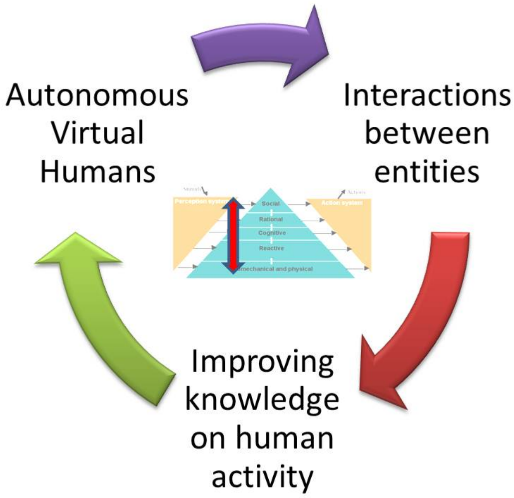

Figure 2: Research path of MimeTIC: coupling analysis and synthesis of human activity enables us to create more realistic autonomous characters and to evaluate assumptions about human motion control.

In this research path, **improving knowledge on human activity** allows us to highlight fundamental assumptions about natural control of human activities. These contributions can be promoted in e.g. biomechanics, motion sciences, neurosciences. According to these assumptions, we propose new algorithms for controlling **autonomous virtual humans**. The virtual humans can perceive their environment and decide of the most natural action to reach a given goal. This work is promoted in computer animation, virtual reality and has some applications in robotics through collaborations. Once autonomous virtual humans have the ability to act as real humans would in the same situation, it is possible to make them **interact with others**, i.e., autonomous characters (for crowds or group simulations) as well as real users. The key idea here is to analyze to what extent the assumptions proposed at the first stage lead to natural interactions with real users. This process enables the validation of both our assumptions and our models.

Among all the problems and challenges described above, MimeTIC focuses on the following domains of research:

- **motion sensing** which is a key issue to extract information from raw motion capture systems and thus to propose assumptions on how people control their activity,
- **human activity & virtual reality**, which is explored through sports application in MimeTIC. This domain enables the design of new methods for analyzing the perception-action coupling in human activity, and to validate whether the autonomous characters lead to natural interactions with users,
- **interactions** in small and large groups of individuals, to understand and model interactions with lot of individual variability such as in crowds,
- **virtual storytelling** which enables us to design and simulate complex scenarios involving several humans who have to satisfy numerous complex constraints (such as adapting to the real-time environment in order to play an imposed scenario), and to design the coupling with the camera scenario to provide the user with a real cinematographic experience,
- **biomechanics** which is essential to offer autonomous virtual humans who can react to physical constraints in order to reach high-level goals, such as maintaining balance in dynamic situations or selecting a natural motor behavior among the whole theoretical solution space for a given task,
- **autonomous characters** which is a transversal domain that can reuse the results of all the other domains to make these heterogeneous assumptions and models provide the character with natural behaviors and autonomy.

3 Research program

3.1 Biomechanics and Motion Control

Human motion control is a highly complex phenomenon that involves several layered systems, as shown in Figure 3. Each layer of this controller is responsible for dealing with perceptual stimuli in order to decide the actions that should be applied to the human body and his environment. Due to the intrinsic complexity of the information (internal representation of the body and mental state, external representation of the environment) used to perform this task, it is almost impossible to model all the possible states of the system. Even for simple problems, there generally exists an infinity of solutions. For example, from the biomechanical point of view, there are much more actuators (i.e. muscles) than degrees of freedom leading to an infinity of muscle activation patterns for a unique joint rotation. From the reactive point of view there exists an infinity of paths to avoid a given obstacle in navigation tasks. At each layer, the key problem is to understand how people select one solution among these infinite state spaces. Several scientific domains have addressed this problem with specific points of view, such as physiology, biomechanics, neurosciences and psychology.

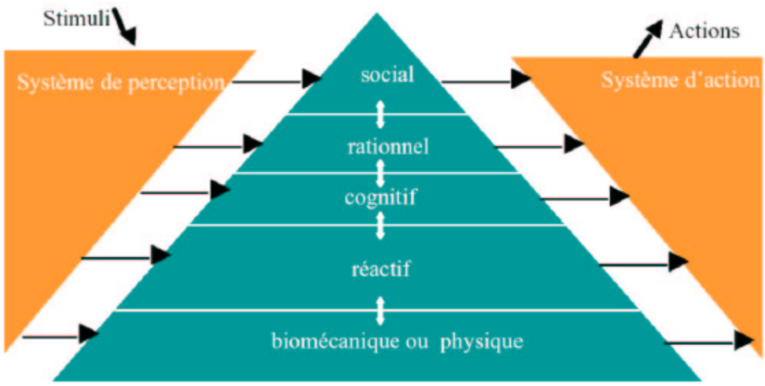

Figure 3: Layers of the motion control natural system in humans.

In biomechanics and physiology, researchers have proposed hypotheses based on accurate joint modeling (to identify the real anatomical rotational axes), energy minimization, force and torques minimization, comfort maximization (i.e. avoiding joint limits), and physiological limitations in muscle force production. All these constraints have been used in optimal controllers to simulate natural motions. The main problem is thus to define how these constraints are composed altogether such as searching the weights used to linearly combine these criteria in order to generate a natural motion. Musculoskeletal models are stereotyped examples for which there exists an infinity of muscle activation patterns, especially when dealing with antagonist muscles. An unresolved problem is to define how to use the above criteria to retrieve the actual activation patterns, while optimization approaches still leads to unrealistic ones. It is still an open problem that will require multidisciplinary skills including computer simulation, constraint solving, biomechanics, optimal control, physiology and neuroscience.

In neuroscience, researchers have proposed other theories, such as coordination patterns between joints driven by simplifications of the variables used to control the motion. The key idea is to assume that instead of controlling all the degrees of freedom, people control higher level variables which correspond to combinations of joint angles. In walking, data reduction techniques such as Principal Component Analysis have shown that lower-limb joint angles are generally projected on a unique plane whose angle in the state space is associated with energy expenditure. Although knowledge exists for specific motions, such as locomotion or grasping, this type of approach is still difficult to generalize. The key problem is that many variables are coupled and it is very difficult to objectively study the behavior of a unique variable in various motor tasks. Computer simulation is a promising method to evaluate such type of assumptions as it enables to accurately control all the variables and to check if it leads to natural movements.

Neuroscience also addresses the problem of coupling perception and action by providing control laws based on visual cues (or any other senses), such as determining how the optical flow is used to control direction in navigation tasks, while dealing with collision avoidance or interception. Coupling of the control variables is enhanced in this case as the state of the body is enriched by the large amount of external information that the subject can use. Virtual environments inhabited with autonomous characters whose behavior is driven by motion control assumptions, is a promising approach to solve this problem. For example, an interesting issue in this field is to navigate in an environment inhabited with other people. Typically, avoiding static obstacles along with other people moving inside that environment is a combinatory problem that strongly relies on the coupling between perception and action.

One of the main objectives of MimeTIC is to enhance knowledge on human motion control by developing innovative experiments based on computer simulation and immersive environments. To this end, designing experimental protocols is a key point and some of the researchers in MimeTIC have developed this skill in biomechanics and perception-action coupling. Associating these researchers to experts in virtual human simulation, computational geometry and constraints solving allows us to contribute to enhance fundamental knowledge in human motion control.

3.2 Experiments in Virtual Reality

Understanding interactions between humans is challenging because it addresses many complex phenomena including perception, decision-making, cognition and social behaviors. Moreover, all these phenomena are difficult to isolate in real situations, and it is therefore highly complex to understand their individual influence on these human interactions. It is then necessary to find an alternative solution that can standardize the experiments and that allows the modification of only one parameter at a time. Video was first used since the displayed experiment is perfectly repeatable and cut-offs (stop of the video at a specific time before its end) allow having temporal information. Nevertheless, the absence of adapted viewpoint and stereoscopic vision does not provide depth information that are very meaningful. Moreover, during video recording sessions, a real human acts in front of a camera and not in front of an opponent. That interaction is then not a real interaction between humans.

Virtual Reality (VR) systems allow full standardization of the experimental situations and the complete control of the virtual environment. It enables to modify only one parameter at a time and observe its influence on the perception of the immersed subject. VR can then be used to understand what information is picked up to make a decision. Moreover, cut-offs can also be used to obtain temporal information about when information is picked up. When the subject can react as in a real situation, his movement (captured in real time) provides information about his reactions to the modified parameter. Not only is the perception studied, but the complete perception-action loop. Perception and action are indeed coupled and influence each other as suggested by Gibson in 1979.

Finally, VR also allows the validation of virtual human models. Some models are indeed based on the interaction between the virtual character and the other humans, such as a walking model. In that case, there are two ways to validate it. They can be compared to real data (e.g. real trajectories of pedestrians). But such data are not always available and are difficult to get. The alternative solution is then to use VR. The validation of the realism of the model is then done by immersing a real subject into a virtual environment in which a virtual character is controlled by the model. Its evaluation is then deduced from how the immersed subject reacts when interacting with the model and how realistic he feels the virtual character is.

3.3 Computer Animation

Computer animation is the branch of computer science devoted to models for the representation and simulation of the dynamic evolution of virtual environments. A first focus is the animation of virtual characters (behavior and motion). Through a deeper understanding of interactions using VR and through better perceptive, biomechanical and motion control models to simulate the evolution of dynamic systems, the Mimetic team has the ability to build more realistic, efficient and believable animations. Perceptual study also enables us to focus computation time on relevant information (i.e. leading to ensure natural motion from the perceptual points of view) and save time for unperceived details. The underlying challenges are (i) the computational efficiency of the system which needs to run in real-time in many situations, (ii) the capacity of the system to generalise/adapt to new situations for which data were not available, or models were not defined for, and (iii) the variability of the models, i.e. their ability to handle many body morphologies and generate variations in motions that would be specific to each virtual character.

In many cases, however, these challenges cannot be addressed in isolation. Typically, character behaviors also depend on the nature and the topology of the environment they are surrounded by. In essence, a character animation system should also rely on smarter representations of the environments, in order to better perceive the environment itself, and take contextualised decisions. Hence the animation of virtual characters in our context often requires to be coupled with models to represent the environment, to reason, and to plan both at a geometric level (can the character reach this location), and at a semantic level (should it use the sidewalk, the stairs, or the road). This represents the second focus. Underlying challenges are the ability to offer a compact -yet precise- representation on which efficient path, motion planning and high-level reasoning can be performed.

Finally, a third scientific focus is digital storytelling. Evolved representations of motions and environments enable realistic animations. It is yet equally important to question how these events should be portrayed, when and under which angle. In essence, this means integrating *discourse models* into *story models*, the story representing the sequence of events which occur in a virtual environment, and the discourse representing how this story should be displayed (i.e. which events to show in which order and with which viewpoint). Underlying challenges are pertained to:

- narrative discourse representations,
- projections of the discourse into the geometry, planning camera trajectories and planning cuts between the viewpoints,
- means to interactively control the unfolding of the discourse.

By therefore establishing the foundations to build bridges between the high-level narrative structures, the semantic/geometric planning of motions and events, and low-level character animations, the Mimetic team adopts a principled and all-inclusive approach to the animation of virtual characters.

4 Application domains

4.1 Animation, Autonomous Characters and Digital Storytelling

Computer Animation is one of the main application domains of the research work conducted in the MimeTIC team, in particular in relation to the entertainment and game industries. In these domains, creating virtual characters that are able to replicate real human motions and behaviours still highlights unanswered key challenges, especially as virtual characters are required to populate virtual worlds. For instance, virtual characters are used to replace secondary actors and generate highly populated scenes that would be hard and costly to produce with real actors. This requires to create high quality replicas that appear, move and behave both individually and collectively like real humans. The three key challenges for the MimeTIC team are therefore:

- to create natural animations (i.e., virtual characters that move like real humans),
- to create autonomous characters (i.e., that behave like real humans),
- to orchestrate the virtual characters so as to create interactive stories.

First, our challenge is to create animations of virtual characters that are natural, i.e. moving like a real human would. This challenge covers several aspects of Character Animation depending on the context of application, e.g., producing visually plausible or physically correct motions, producing natural motion sequences, etc. Our goal is therefore to develop novel methods for animating virtual characters, based on motion capture, data-driven approaches, or learning approaches. However, because of the complexity of human motion (number of degrees of freedom that can be controlled), resulting animations are not necessarily physically, biomechanically, or visually plausible. For instance, current physics-based approaches produce physically correct motions but not necessarily perceptually plausible ones. All these reasons are why most entertainment industries (gaming and movie production for example) still mainly rely on manual animation. Therefore, research in MimeTIC on character animation is also conducted with the goal of validating the results from objective standpoint (physical, biomechanical) as well as subjective one (visual plausibility).

Second, one of the main challenges in terms of autonomous characters is to provide a unified architecture for the modeling of their behavior. This architecture includes perception, action and decisional parts. This decisional part needs to mix different kinds of models, acting at different time scales and working with different natures of data, ranging from numerical (motion control, reactive behaviors) to symbolic (goal oriented behaviors, reasoning about actions and changes). For instance, autonomous characters play the role of actors that are driven by a scenario in video games and virtual storytelling. Their autonomy allows them to react to unpredictable user interactions and adapt their behavior accordingly. In the field of simulation, autonomous characters are used to simulate the behavior of humans in different kinds of situations. They enable to study new situations and their possible outcomes. In the MimeTIC team, our focus is therefore not to reproduce the human intelligence but to propose an architecture making it possible to model credible behaviors of anthropomorphic virtual actors evolving/moving in real-time in virtual worlds. The latter can represent particular situations studied by psychologists of the behavior or to correspond to an imaginary universe described by a scenario writer. The proposed architecture should mimic all the human intellectual and physical functions.

Finally, interactive digital storytelling, including novel forms of edutainment and serious games, provides access to social and human themes through stories which can take various forms and contains opportunities for massively enhancing the possibilities of interactive entertainment, computer games and digital applications. It provides chances for redefining the experience of narrative through interactive simulations of computer-generated story worlds and opens many challenging questions at the overlap between computational narratives, autonomous behaviours, interactive control, content generation and authoring tools. Of particular interest for the MimeTIC research team, virtual storytelling triggers challenging opportunities in providing effective models for enforcing autonomous behaviours for characters in complex 3D environments. Offering both low-level capacities to characters such as perceiving the environments, interacting with the environment itself and reacting to changes in the topology, on which to build higher-levels such as modelling abstract representations for efficient reasoning, planning paths and activities, modelling cognitive states and behaviours requires the provision of expressive, multi-level and efficient computational models. Furthermore virtual storytelling requires the seamless control of the balance between the autonomy of characters and the unfolding of the story through the narrative discourse. Virtual storytelling also raises challenging questions on the conveyance of a narrative through interactive or automated control of the cinematography (how to stage the characters, the lights and the cameras). For example, estimating visibility of key subjects, or performing motion planning for cameras and lights are central issues for which have not received satisfactory answers in the literature.

4.2 Fidelity of Virtual Reality

VR is a powerful tool for perception-action experiments. VR-based experimental platforms allow exposing a population to fully controlled stimuli that can be repeated from trial to trial with high accuracy. Factors can be isolated and objects manipulations (position, size, orientation, appearance, ..) are easy to perform. Stimuli can be interactive and adapted to participants' responses. Such interesting features allow researchers to use VR to perform experiments in sports, motion control, perceptual control laws, spatial cognition as well as person-person interactions. However, the interaction loop between users and their environment differs in virtual conditions in comparison with real conditions. When a user interacts in an environment, movement from action and perception are closely related. While moving, the perceptual system (vision, proprioception,..) provides feedback about the users' own motion and information about the surrounding environment. That allows the user to adapt his/her trajectory to sudden changes in the environment and generate a safe and efficient motion. In virtual conditions, the interaction loop is more complex because it involves several material aspects.

First, the virtual environment is perceived through a numerical display which could affect the available information and thus could potentially introduce a bias. For example, studies observed a distance compression effect in VR, partially explained by the use of a Head Mounted Display with reduced field of view and exerting a weight and torques on the user's head. Similarly, the perceived velocity in a VR environment differs from the real world velocity, introducing an additional bias. Other factors, such as the image contrast, delays in the displayed motion and the point of view can also influence efficiency in VR. The second point concerns the user's motion in the virtual world. The user can actually move if the virtual room is big enough or if wearing a head mounted display. Even with a real motion, authors showed that walking speed is decreased, personal space size is modified and navigation in VR is performed with increased gait instability. Although natural locomotion is certainly the most ecological approach, the physical limited size of VR setups prevents from using it most of the time. Locomotion interfaces are therefore required. They are made up of two components, a locomotion metaphor (device) and a transfer function (software), that can also introduce bias in the generated motion. Indeed, the actuating movement of the locomotion metaphor can significantly differ from real walking, and the simulated motion depends on the transfer function applied. Locomotion interfaces cannot usually preserve all the sensory channels involved in locomotion.

When studying human behavior in VR, the aforementioned factors in the interaction loop potentially introduce bias both in the perception and in the generation of motor behavior trajectories. MimeTIC is working on the mandatory step of VR validation to make it usable for capturing and analyzing human motion.

4.3 Motion Sensing of Human Activity

Recording human activity is a key point of many applications and fundamental works. Numerous sensors and systems have been proposed to measure positions, angles or accelerations of the user's body parts. Whatever the system is, one of the main problems is to be able to automatically recognize and analyze the user's performance according to poor and noisy signals. Human activity and motion are subject to variability: intra-variability due to space and time variations of a given motion, but also inter-variability due to different styles and anthropometric dimensions. MimeTIC has addressed the above problems in two main directions.

First, we have studied how to recognize and quantify motions performed by a user when using accurate systems such as Vicon (product from Oxford Metrics), Qualisys, or Optitrack (product from Natural Point) motion capture systems. These systems provide large vectors of accurate information. Due to the size of the state vector (all the degrees of freedom) the challenge is to find the compact information (named features) that enables the automatic system to recognize the performance of the user. Whatever the method used, finding these relevant features that are not sensitive to intra-individual and inter-individual variability is a challenge. Some researchers have proposed to manually edit these features (such as a Boolean value stating if the arm is moving forward or backward) so that the expertise of the designer is directly linked with the success ratio. Many proposals for generic features have been proposed, such as using Laban notation which was introduced to encode dancing motions. Other approaches tend to use machine learning to automatically extract these features. However most of the proposed approaches were used to seek a database for motions, whose properties correspond to the features of the user's performance (named motion retrieval approaches). This does not ensure the retrieval of the exact performance of the user but a set of motions with similar properties.

Second, we wish to find alternatives to the above approach which is based on analyzing accurate and complete knowledge of joint angles and positions. Hence new sensors, such as depth-cameras (Kinect, product from Microsoft) provide us with very noisy joint information but also with the surface of the user. Classical approaches would try to fit a skeleton into the surface in order to compute joint angles which, again, lead to large state vectors. An alternative would be to extract relevant information directly from the raw data, such as the surface provided by depth cameras. The key problem is that the nature of these data may be very different from classical representation of human performance. In MimeTIC, we try to address this problem in some application domains that require picking specific information, such as gait asymmetry or regularity for clinical analysis of human walking.

4.4 Sports

Sport is characterized by complex displacements and motions. One main objective is to understand the determinants of performance through the analysis of the motion itself. In the team, different sports have been studied such as the tennis serve, where the goal was to understand the contribution of each segment of the body in the performance but also the risk of injuries as well as other situation in cycling, swimming, fencing or soccer. Sport motions are dependent on visual information that the athlete can pick up in his environment, including the opponent's actions. Perception is thus fundamental to the performance. Indeed, a sportive action, as unique, complex and often limited in time, requires a selective gathering of information. This perception is often seen as a prerogative for action. It then takes the role of a passive collector of information. However, as mentioned by Gibson in 1979, the perception-action relationship should not be considered sequentially but rather as a coupling: we perceive to act but we must act to perceive. There would thus be laws of coupling between the informational variables available in the environment and the motor responses of a subject. In other words, athletes have the ability to directly perceive the opportunities of action directly from the environment. Whichever school of thought considered, VR offers new perspectives to address these concepts by complementary using real time motion capture of the immersed athlete.

In addition to better understand sports and interactions between athletes, VR can also be used as a training environment as it can provide complementary tools to coaches. It is indeed possible to add visual or auditory information to better train an athlete. The knowledge found in perceptual experiments can be for example used to highlight the body parts that are important to look at, in order to correctly anticipate the opponent's action.

4.5 Ergonomics

The design of workstations nowadays tends to include assessment steps in a Virtual Environment (VE) to evaluate ergonomic features. This approach is more cost-effective and convenient since working directly on the Digital Mock-Up (DMU) in a VE is preferable to constructing a real physical mock-up in a Real Environment (RE). This is substantiated by the fact that a Virtual Reality (VR) set-up can be easily modified, enabling quick adjustments of the workstation design. Indeed, the aim of integrating ergonomics evaluation tools in VEs is to facilitate the design process, enhance the design efficiency, and reduce the costs.

The development of such platforms asks for several improvements in the field of motion analysis and VR. First, interactions have to be as natural as possible to properly mimic the motions performed in real environments. Second, the fidelity of the simulator also needs to be correctly evaluated. Finally, motion analysis tools have to be able to provide in real-time biomechanics quantities usable by ergonomists to analyse and improve the working conditions.

In real working condition, motion analysis and musculoskeletal risk assessment raise also many scientific and technological challenges. Similarly to virtual reality, fidelity of the working process may be affected by the measurement method. Wearing sensors or skin markers, together with the need of frequently calibrating the assessment system may change the way workers perform the tasks. Whatever the measurement is, classical ergonomic assessments generally address one specific parameter, such as posture, or force, or repetitions…, which makes it difficult to design a musculoskeletal risk factor that actually represents this risk. Another key scientific challenge is then to design new indicators that better capture the risk of musculoskeletal disorders. However, this indicator has to deal with the trade-off between accurate biomechanical assessment and the difficulty to get reliable and required information in real working conditions.

4.6 Locomotion and Interactions between walkers

Modeling and simulating locomotion and interactions between walkers is a very active, complex and competitive domain, being investigating by various disciplines such as mathematics, cognitive sciences, physics, computer graphics, rehabilitation etc. Locomotion and interactions between walkers are by definition at the very core of our society since they represent the basic synergies of our daily life. When walking in the street, we should produce a locomotor movement while taking information about our surrounding environment in order to interact with people, move without collision, alone or in a group, intercept, meet or escape to somebody. MimeTIC is an international key contributor in the domain of understanding and simulating locomotion and interactions between walkers. By combining an approach based on Human Movement Sciences and Computer Sciences, the team focuses on locomotor invariants which characterize the generation of locomotor trajectories. We also conduct challenging experiments focusing on visuo-motor coordination involved during interactions between walkers both using real and virtual set-ups. One main challenge is to consider and model not only the "average" behaviour of healthy younger adult but also extend to specific populations considering the effect of pathology or the effect of age (kids, older adults). As a first example, when patients cannot walk efficiently, in particular those suffering from central nervous system affections, it becomes very useful for practitioners to benefit from an objective evaluation of their capacities. To facilitate such evaluations, we have developed two complementary indices, one based on kinematics and the other one on muscle activations. One major point of our research is that such indices are usually only developed for children whereas adults with these affections are much more numerous. We extend this objective evaluation by using person-person interaction paradigm which allows studying visuo-motor strategies deficit in these specific populations.

Another fundamental question is the adaptation of the walking pattern according to anatomical constraints, such as pathologies in orthopedics, or adaptation to various human and non-human primates in paleoanthropoly. Hence, the question is to predict plausible locomotion according to a given morphology. This raises fundamental questions about the variables that are regulated to control gait: balance control, minimum energy, minimum jerk... In MimeTIC we develop models and simulators to efficiently test hypotheses on gait control for given morphologies.

5 Highlights of the year

2024 is the last year for MimeTIC, created in 2012. MimeTIC has been positively evaluated, and a new project arises, supported by Charles Pontonnier. This new team "ComBo" (computational biomechanics) will continue the human motion analysis and synthesis loop, with a strong focus on the physical interaction between humans ans their environment. ComBo will address new topics, requiring to reinforce the skills in sports sciences and biomechanics. ComBo has received a positive feedback from the evaluation process and is scheduled to start in January 2025.

In 2024, we have recruited one CRCN Inria researcher, Nolwenn Fougeron. This is an important step for the creation of the new team, ComBo, as Nolwenn is bringing new expertise in soft tissue modeling and simulation. It opens new research avenues in the context of modeling and simulating physical interactions between a human and his environment.

MimeTIC was also strongly involved in events related to sports, especially in the context of the Paris2024 Olympic Games. We were present at this major international event, as exhibitors (hosted by the French Ministery of Research) to demonstrate the results of the ShareSpace EU project. More than 2000 citizens experienced our VR demo, and 500 of them were volunteer to collect the data and take part of a scientific experiment. We also widely disseminated the work of the team in the domain of sports, such as organizing the Sport Unlimitech major event in Rennes in June, or taking part of several wide public audience journals, radio and TV shows.

Organisation of the Sports Physics Congress 2024 at the Inria Congress Center (Conference Chair: Charles Pontonnier): The main objective of the Sports Physics conferences, which take place every Summer Olympic years since 2012, is to mix physics, mechanics, biomechanics, mathematics, computer sciences, data sciences and physiology to propose practical solutions to problems identified on field by coaches, medical teams and athletes. The attendees of the conference have different origins from fundamental and applied researchers to sport scientists, athletes and coaches in order to promote exchanges and collaborations. Since 2024 is special for France, this edition was also dedicated to the evaluation of the scientific impact of science in the Olympic results.

6 New software, platforms, open data

6.1 New software

6.1.1 AsymGait

Name: Asymmetry index for clinical gait analysis based on depth images

Keywords: Motion analysis, Kinect, Clinical analysis

Scientific Description: The system uses depth images delivered by the Microsoft Kinect to retrieve the gait cycles first. To this end it is based on a analyzing the knees trajectories instead of the feet to obtain more robust gait event detection. Based on these cycles, the system computes a mean gait cycle model to decrease the effect of noise of the system. Asymmetry is then computed at each frame of the gait cycle as the spatial difference between the left and right parts of the body. This information is computed for each frame of the cycle.

Functional Description: AsymGait is a software package that works with Microsoft Kinect data, especially depth images, in order to carry-out clinical gait analysis. First it identifies the main gait events using the depth information (footstrike, toe-off) to isolate gait cycles. Then it computes a continuous asymmetry index within the gait cycle. Asymmetry is viewed as a spatial difference between the two sides of the body.

Contact: Franck Multon

Participants: Edouard Auvinet, Franck Multon

6.1.2 Cinematic Viewpoint Generator

Keyword: 3D animation

Functional Description: The software, developed as an API, provides a mean to automatically compute a collection of viewpoints over one or two specified geometric entities, in a given 3D scene, at a given time. These viewpoints satisfy classical cinematographic framing conventions and guidelines including different shot scales (from extreme long shot to extreme close-up), different shot angles (internal, external, parallel, apex), and different screen compositions (thirds,fifths, symmetric of di-symmetric). The viewpoints allow to cover the range of possible framings for the specified entities. The computation of such viewpoints relies on a database of framings that are dynamically adapted to the 3D scene by using a manifold parametric representation and guarantee the visibility of the specified entities. The set of viewpoints is also automatically annotated with cinematographic tags such as shot scales, angles, compositions, relative placement of entities, line of interest.

Contact: Marc Christie

Participants: Christophe Lino, Emmanuel Badier, Marc Christie

Partners: Université d'Udine, Université de Nantes

6.1.3 CusToM

Name: Customizable Toolbox for Musculoskeletal simulation

Keywords: Biomechanics, Dynamic Analysis, Kinematics, Simulation, Mechanical multi-body systems

Scientific Description: The present toolbox aims at performing a motion analysis thanks to an inverse dynamics method.

Before performing motion analysis steps, a musculoskeletal model is generated. Its consists of, first, generating the desire anthropometric model thanks to models libraries. The generated model is then kinematical calibrated by using data of a motion capture. The inverse kinematics step, the inverse dynamics step and the muscle forces estimation step are then successively performed from motion capture and external forces data. Two folders and one script are available on the toolbox root. The Main script collects all the different functions of the motion analysis pipeline. The Functions folder contains all functions used in the toolbox. It is necessary to add this folder and all the subfolders to the Matlab path. The Problems folder is used to contain the different study. The user has to create one subfolder for each new study. Once a new musculoskeletal model is used, a new study is necessary. Different files will be automaticaly generated and saved in this folder. All files located on its root are related to the model and are valuable whatever the motion considered. A new folder will be added for each new motion capture. All files located on a folder are only related to this considered motion.

Functional Description: Inverse kinematics Inverse dynamics Muscle forces estimation External forces prediction

Publications: hal-02268958, hal-02088913, hal-02109407, hal-01904443, hal-02142288, hal-01988715, hal-01710990

Contact: Charles Pontonnier

Participants: Antoine Muller, Charles Pontonnier, Georges Dumont, Pierre Puchaud, Anthony Sorel, Claire Livet, Louise Demestre

6.1.4 Directors Lens Motion Builder

Keywords: Previzualisation, Virtual camera, 3D animation

Functional Description: Directors Lens Motion Builder is a software plugin for Autodesk's Motion Builder animation tool. This plugin features a novel workflow to rapidly prototype cinematographic sequences in a 3D scene, and is dedicated to the 3D animation and movie previsualization industries. The workflow integrates the automated computation of viewpoints (using the Cinematic Viewpoint Generator) to interactively explore different framings of the scene, proposes means to interactively control framings in the image space, and proposes a technique to automatically retarget a camera trajectory from one scene to another while enforcing visual properties. The tool also proposes to edit the cinematographic sequence and export the animation. The software can be linked to different virtual camera systems available on the market.

Contact: Marc Christie

Participants: Christophe Lino, Emmanuel Badier, Marc Christie

Partner: Université de Rennes 1

6.1.5 Kimea

Name: Kinect IMprovement for Egronomics Assessment

Keywords: Biomechanics, Motion analysis, Kinect

Scientific Description: Kimea consists in correcting skeleton data delivered by a Microsoft Kinect in an ergonomics purpose. Kimea is able to manage most of the occlultations that can occur in real working situation, on workstations. To this end, Kimea relies on a database of examples/poses organized as a graph, in order to replace unreliable body segments reconstruction by poses that have already been measured on real subject. The potential pose candidates are used in an optimization framework.

Functional Description: Kimea gets Kinect data as input data (skeleton data) and correct most of measurement errors to carry-out ergonomic assessment at workstation.

Publications: hal-01612939v1, hal-01393066v1, hal-01332716v1, hal-01332711v2, hal-01095084v1

Contact: Franck Multon

Participants: Franck Multon, Hubert Shum, Pierre Plantard

Partner: Faurecia

6.1.6 Populate

Keywords: Behavior modeling, Agent, Scheduling

Scientific Description: The software provides the following functionalities:

- A high level XML dialect that is dedicated to the description of agents activities in terms of tasks and sub activities that can be combined with different kind of operators: sequential, without order, interlaced. This dialect also enables the description of time and location constraints associated to tasks.

- An XML dialect that enables the description of agent's personal characteristics.

- An informed graph describes the topology of the environment as well as the locations where tasks can be performed. A bridge between TopoPlan and Populate has also been designed. It provides an automatic analysis of an informed 3D environment that is used to generate an informed graph compatible with Populate.

- The generation of a valid task schedule based on the previously mentioned descriptions.

With a good configuration of agents characteristics (based on statistics), we demonstrated that tasks schedules produced by Populate are representative of human ones. In conjunction with TopoPlan, it has been used to populate a district of Paris as well as imaginary cities with several thousands of pedestrians navigating in real time.

Functional Description: Populate is a toolkit dedicated to task scheduling under time and space constraints in the field of behavioral animation. It is currently used to populate virtual cities with pedestrian performing different kind of activities implying travels between different locations. However the generic aspect of the algorithm and underlying representations enable its use in a wide range of applications that need to link activity, time and space. The main scheduling algorithm relies on the following inputs: an informed environment description, an activity an agent needs to perform and individual characteristics of this agent. The algorithm produces a valid task schedule compatible with time and spatial constraints imposed by the activity description and the environment. In this task schedule, time intervals relating to travel and task fulfillment are identified and locations where tasks should be performed are automatically selected.

Contact: Fabrice Lamarche

Participants: Carl-Johan Jorgensen, Fabrice Lamarche

6.1.7 PyNimation

Keywords: Moving bodies, 3D animation, Synthetic human

Scientific Description: PyNimation is a python-based open-source (AGPL) software for editing motion capture data which was initiated because of a lack of open-source software enabling to process different types of motion capture data in a unified way, which typically forces animation pipelines to rely on several commercial software. For instance, motions are captured with a software, retargeted using another one, then edited using a third one, etc. The goal of Pynimation is therefore to bridge the gap in the animation pipeline between motion capture software and final game engines, by handling in a unified way different types of motion capture data, providing standard and novel motion editing solutions, and exporting motion capture data to be compatible with common 3D game engines (e.g., Unity, Unreal). Its goal is also simultaneously to provide support to our research efforts in this area, and it is therefore used, maintained, and extended to progressively include novel motion editing features, as well as to integrate the results of our research projects. At a short term, our goal is to further extend its capabilities and to share it more largely with the animation/research community.

Functional Description: PyNimation is a framework for editing, visualizing and studying skeletal 3D animations, it was more particularly designed to process motion capture data. It stems from the wish to utilize Python's data science capabilities and ease of use for human motion research.

In its version 1.0, Pynimation offers the following functionalities, which aim to evolve with the development of the tool : - Import / Export of FBX, BVH, and MVNX animation file formats - Access and modification of skeletal joint transformations, as well as a certain number of functionalities to manipulate these transformations - Basic features for human motion animation (under development, but including e.g. different methods of inverse kinematics, editing filters, etc.). - Interactive visualisation in OpenGL for animations and objects, including the possibility to animate skinned meshes

URL: https://gitlab.inria.fr/lhoyet/pynimation

Contact: Ludovic Hoyet

6.1.8 The Theater

Keywords: 3D animation, Interactive Scenarios

Functional Description: The Theater is a software framework to develop interactive scenarios in virtual 3D environements. The framework provides means to author and orchestrate 3D character behaviors and simulate them in real-time. The tools provides a basis to build a range of 3D applications, from simple simulations with reactive behaviors, to complex storytelling applications including narrative mechanisms such as flashbacks.

Contact: Marc Christie

Participant: Marc Christie

6.2 New platforms

6.2.1 Immerstar Platform

Participants: Georges Dumont *(contact)*, Ronan Gaugne, Anthony Sorel, Richard Kulpa.

With the two platforms of virtual reality, Immersia) and Immermove Immermove, grouped under the name Immerstar, the team has access to high level scientific facilities. This equipment benefits the research teams of the center and has allowed them to extend their local, national and international collaborations. The Immerstar platform was granted by a Inria CPER funding for 2015-2019 that enabled important evolutions of the equipment. In 2016, the first technical evolutions have been decided and, in 2017, these evolutions have been implemented. On one side, for Immermove, the addition of a third face to the immersive space, and the extension of the Vicon tracking system have been realized and continued this year with 23 new cameras. And, on the second side, for Immersia, the installation of WQXGA laser projectors with augmented global resolution, of a new tracking system with higher frequency and of new computers for simulation and image generation in 2017. In 2018, a Scale One haptic device has been installed. It allows, as in the CPER proposal, one or two handed haptic feedback in the full space covered by Immersia and possibility of carrying the user. Based on these supports, in 2020, we participated to a PIA3-Equipex+ proposal. This proposal CONTINUUM involves 22 partners, has been succesfully evaluated and will be granted. The CONTINUUM project will create a collaborative research infrastructure of 30 platforms located throughout France, to advance interdisciplinary research based on interaction between computer science and the human and social sciences. Thanks to CONTINUUM, 37 research teams will develop cutting-edge research programs focusing on visualization, immersion, interaction and collaboration, as well as on human perception, cognition and behaviour in virtual/augmented reality, with potential impact on societal issues. CONTINUUM enables a paradigm shift in the way we perceive, interact, and collaborate with complex digital data and digital worlds by putting humans at the center of the data processing workflows. The project will empower scientists, engineers and industry users with a highly interconnected network of high-performance visualization and immersive platforms to observe, manipulate, understand and share digital data, real-time multi-scale simulations, and virtual or augmented experiences. All platforms will feature facilities for remote collaboration with other platforms, as well as mobile equipment that can be lent to users to facilitate onboarding. The kick-off meeting of continuum has been held in 2022, January the 14th. A global meeting was held in 2022, July the 5th and 6th.

7 New results

7.1 Outline

In 2024, MimeTIC has maintained its activity in motion analysis, modelling and simulation, to support the idea that these approaches are strongly coupled in a motion analysis-synthesis loop. This idea has been applied to the main application domains of MimeTIC:

- Animation, Autonomous Characters and Digital Storytelling. In this domain, 2024 was a transition period with the starting PhDs of Guillaume Loranchet and Ahmed Abdourahman Mahamoud. As these PhD students started at the end of 2023, they submitted papers in 2024 that are under review when writing this report. Hence, there is no reported results in this domain in this report, for 2024.
- Motion sensing of Human Activity,
- Sports,
- Ergonomics,

7.2 Motion Sensing of Human Activity

MimeTIC has a long experience in motion analysis in laboratory condition. In the MimeTIC project, we proposed to explore how these approaches could be transferred to ecological situations, with a lack of control on the experimental conditions. In 2024, we continued to explore the use of deep learning techniques to capture human performance based on simple RGB or depth images. We also continued exploring estimating biomechanical values from sparse outdoor measuremets.

7.2.1 Pressure insoles assessment for external forces prediction

Participants: Pauline Morin, Georges Dumont *(contact)*, Charles Pontonnier *(contact)*.

Force platforms generally involves a costraint to analyze human movement in the laboratory. Promising methods for estimating ground reaction forces and moments (GRF&M) can overcome this limitation. The most effective family of methods consists of minimizing a cost, constrained by the subject's dynamic equilibrium, for distributing the force over the contact surface on the ground. The detection of contact surfaces over time is dependent on numerous parameters. In this work we proposed to evaluate two contact detection methods: the first based on foot kinematics and the second based on pressure sole data. Optimal parameters for these two methods were identified for walking, running, and sidestep cut tasks. The results show that a single threshold in position or velocity is sufficient to guarantee a good estimate. Using pressure sole data to detect contact improves the estimation of the position of the center of pressure (CoP). Both methods demonstrated a similar level of accuracy in estimating ground reaction forces [18].

7.2.2 Unsupervised Occupancy Learning from Sparse Point Cloud

Participants: Adnane Boukhayma *(contact)*, Amine Ouasfi.

Implicit Neural Representations have gained prominence as a powerful framework for capturing complex data modalities, encompassing a wide range from 3D shapes to images and audio. Within the realm of 3D shape representation, Neural Signed Distance Functions (SDF) have demonstrated remarkable potential in faithfully encoding intricate shape geometry. However, learning SDFs from 3D point clouds in the absence of ground truth supervision remains a very challenging task. In this work [27], we propose a method to infer occupancy fields instead of SDFs as they are easier to learn from sparse inputs. We leverage a margin-based uncertainty measure to differentially sample from the decision boundary of the occupancy function and supervise the sampled boundary points using the input point cloud. We further stabilize the optimization process at the early stages of the training by biasing the occupancy function towards minimal entropy fields while maximizing its entropy at the input point cloud. Through extensive experiments and evaluations, we illustrate the efficacy of our proposed method, highlighting its capacity to improve implicit shape inference with respect to baselines and the state-of-the-art using synthetic and real data.

7.3 Sports

MimeTIC promotes the idea of coupling motion analysis and synthesis in various domains, especially sports. More specifically, we have a long experience and international leadership in using Virtual Reality for analyzing and training sports performance. In 2024, we continued to explore how enhancing the use of VR to design original training system.

We also initiated some simulation works to better charactierize the interaction between a user and his physical environment, such as interactions between swimmers, diving boards, or vault.

7.3.1 VR for training perceptual-motor skills of boxers and relay runners for Paris 2024 Olympic games

Participants: Richard Kulpa *(contact)*, Annabelle Limballe.

The revolution in digital technologies, and in particular Virtual Reality, in the field of sport has opened up new perspectives for the creation of new modalities for analyzing and training the skills underlying performance. Virtual Reality allows for the standardization, control and variation (even beyond real conditions) of stimuli while simultaneously quantifying performance. This provides the opportunity to offer specific training sessions, complementary to traditional training ones. In addition, in order to continuously improve their performances, athletes need to train more and more but they may reach their physical limits. Virtual Reality can create new training modalities that allow them to continue training while minimising the risk of injury (for example, due to the repetition of high-intensity work in races for a 4x100m relay or due to the impacts of defensive training in boxing). It may also be relevant for injured athletes who cannot physically practice their discipline but need to continue to train perceptually and cognitively by confronting field situations.

In the PPR REVEA project, we created an interdisciplinary framework to optimize the training of anticipation of high-level athletes [17]. We implemented it in the French Boxing and Athletics federations to train athletes' anticipation skills in their preparation for the Paris 2024 Olympic Games. In the 4x100m relay, the team's performance partly depends on the athletes' ability to synchronize their movements and therefore initiate their race at the right moment, before the partner arrives in the relay transmission zone, despite the pressure exerted by the opponents. The Virtual Reality training protocols are therefore designed to train each athlete to initiate his or her race at the right moment, with a tireless and always available avatar, based on the motion capture of real sprinters, whose race characteristics can be configured in terms of speed, lane, curvature, gender, etc. The first work identified the mechanisms underlying anticipation skills in the 4x100m relay. The second study showed the importance of variability in such a training [33]. In boxing, the federation wants to improve boxers' anticipation skills in defensive situations without making them undergo repetitive blows that could injure them, which is impossible in real training. Virtual Reality training protocols allow boxers to focus on the appropriate information on the opponent, which should enable them to anticipate attacks and adopt the relevant parry. In the last study, we evaluated the impact of gaze-contingent blur on elite boxers performance and gaze behavior [15].

7.3.2 Early gesture detection in untrimmed streams: A controlled CTC approach for reliable decision-making

Participants: Richard Kulpa *(contact)*, William Mocaer.

This work focuses on the problem of online action detection for interactive systems, with a special emphasis on earliness [16]. Online Action Detection (OAD) refers to the challenging task of recognizing gestures in untrimmed, streaming videos where the actions occur in unpredictable orders and durations. To address these challenges, we present a skeleton-based system for OAD incorporating a decision mechanism to accurately detect ongoing gestures. This allows us to provide instance-level output, achieving a high level of stream understanding. This mechanism relies on a novel Connectionist Temporal Classification (CTC) loss design that restricts the path possibilities according to the action boundaries. We also present a mechanism to tune the trade-off between accuracy and earliness according to the needs of the interactive system using a weighted label prior. This system includes a 3D CNN network, referred to as DOLT-C3D, exploiting the spatial-temporal information provided by the euclidean skeleton representation. We extensively evaluate our approach on eight publicly available datasets, demonstrating its superior performance compared to state-of-the-art methods in terms of both accuracy and earliness. We also successfully applied our approach to early 2D gestures detection. Furthermore, our system shows real-time performance, making it a suitable choice for interactive systems.

7.3.3 Pole vault analysis

Participants: Georges Dumont *(contact)*, Guillaume Nicolas, Nicolas Bideau, Victor Restrat.

Pole vaulting is a challenging Olympic discipline that requires speed, strength and technical skills. In order to achieve the best possible performance, the athlete uses the pole of his choice in terms of both length and stiffness. Thus, the athlete-pole interactions must be highly efficient to transform a horizontal displacement into a vertical one. To investigate energy conversion over the time during support phase, 2D video-based approaches is generally preferred but 3D video analysis and motion capture can be also used in rare case. The aim of this preliminary study was to verify the possibility to quantify the pole vaulter's energy transfers in practice using a system with multiple inertial sensor units (IMU) [29, 34]

7.3.4 In-situ motion analysis during swimming training and competition

Participants: Nicolas Bideau *(contact)*, Guillaume Nicolas, Benoit Bideau.

There is a growing trend in swimming, as in many other sports, to monitor human technical skills, and performance during in situ training and competition. To do so, several devices and sensors are becoming more readily available for athletes and allow performance to be quantified more precisely. However, conventional devices such as cameras in swimming suffer from optical occlusions and cumbersome non-automatic data processing making reliable assessment hard to achieve in real conditions.Thus, we developed a deep learning model devoted to the analysis of swimming using a single Inertial Measurement Unit (IMU) attached to the sacrum. The proposed method took high inter- and intra-swimmer variability into account and was set up for the purpose of predicting eight swimming classes at several swimming velocities ranging from low to maximal. The method is able to automatically analyze swimmers with various levels of expertise in the context of in situ training monitoring.

Moreover, race analysis in swimming can support the guidance of training and the adjustment of race strategy through provision of feedbacks to coach. However, in-situ assessment of stroke mechanics in open water swimming is largely constrained by several factors (motion on a large outdoor area, mass start configuration, etc) compromising the use of conventional video. In addition, in order to better understand biomechanical regulations, there is a need for continuous monitoring of stroke parameters all along the race. Using IMU sensors combined with AI algorithm automatically computing biomechanical metrics cycle-to-cycle, we identified stroke regulation profiles and tipping-points in stroke regulation timing during international open water races according to performance level [32].

Performance analysis in swimming requires the identification of individual skills and the way the best swimmers master their movement. Therefore, monitoring their biomechanical abilities through technical assessment is at the heart of the understanding of elite performances. In order to assist eyes-based technical evaluation we developed [13] a data-driven approach to profile biomechanical abilities during sprint front crawl by identifying technical stroke characteristics, in light of performance level. Intra and inter-cyclic 3D kinematical variabilities were clustered using a functional double partition model. Clusters were analysed according to (1) swimming technique using continuous visualisation and discrete features (standard deviation and jerk cost) and (2) performance regarding speed and competition calibre. Moreover, in order to enhance the technical understanding of discriminative pacing skills in swimming, we used IMU sensors and Hierarchical generalized additive models to identify the stroke mechanics regulations that underlie pacing optimization and differentiate final performance in the 400m freestyle across different performance levels [32]. These models depicted both the common patterns shared by all swimmers, and the specific group-deviations by performance leve from population trends.

This research is integrated into the French national research agency program "Sport de Très Haute Performance" aiming at optimizing performances towards the 2024 Olympic and Paralympic Games. Thus, beyond scientific contributions, the solution developed is routinely used by the French Swimmming Federation in the follow-up of high level swimmers during training and competition as it serves as decision support in the context of the preparation of athletes.

7.3.5 Evaluation and monitoring of active drag and propulsive abilities of swimmers in relation with kinematics

Participants: Nicolas Bideau *(contact)*, Guillaume Nicolas, Benoit Bideau.

The aim of this work was to provide insights into optimization of swimming technique while minimizing active drag (AD) by evaluating to what extent the swimming technique affects power production and water resistances. An indirect assessment of AD using semi-tethered conditions has be developed by means on the velocity perturbation method (VPM). This approach was also used to investigate the associations between dryland load-velocity profiles and in-situ (swimming) load-velocity parameters [20]. A method allowing the identification of an optimal subject-specific load which improves AD reliability was also developed. As the for the previous topic, this research is integrated into the French national research agency program "Sport de Très Haute Performance" aiming at optimizing performances towards the 2024 Olympic and Paralympic Games. The results led to routinely on-field evaluation for high level swimmers.

7.3.6 Gym Landing impact analysis

Participants: Charles Pontonnier *(contact)*, Diane Haering, Rebecca Crolan, Suzon Pucheu.

The purpose of this study was to investigate the kinematics and muscle activity of the lower limbs and lumbar spine during the landing of a jump in female gymnasts. Sixteen adult gymnasts performed round-offs followed by a back somersault. Lumbar, hip, and knee joint angles at peak GRF and EMG activity of 4 lumbar spine muscles were recorded. The study reveals a large heterogeneity in the kinematic and muscular strategies used by the gymnasts. A more detailed investigation is required to gain a better understanding of the motor behaviors observed, with a view to potentially improving individualized monitoring during the season and reducing the incidence of injury [22].We also launched a work about the indirect estimation of impact forces through temporal neural networks with encouraging preliminary results.[28].

7.3.7 Comparison of two Qwan ki do punching techniques

Participants: Franck Multon *(contact)*, Charles Pontonnier, François LeFailler.

Qwan Ki Do is derived from Chinese and Vietnamese martial arts, mixing many fighting techniques such as fists, feet, elbows, sweeps, scissors, projections, grabs, locks, self-defense. Technique efficiency is a constant debate, for which masters and coaches have insights and beliefs. In Qwan Ki Do, punching may be performed with a classical fist technique or with an anchoring on the ground through the feet. Coaches think that this latter technique, consisting in voluntary "pushing" on the ground, may be more efficient in terms of striking force and propagation.

To test this assumption, we defined an experimental protocol [25], consisting in striking an instrumented boxing pad, measuring striking force and pad acceleration, motion and ground reaction forces of the striker. 5 experienced (> 3 years) Qwan Ki Do practitionners were recruited to perform 4 series of 10 strikes (jab and cross, with and without anchoring). The anchoring technique was found to generate more power, particularly in the cross strike ($p < 0.01$). Additionally, a consistent finding across both punch types was that the center of mass was lower in the anchoring condition ($p < 0.05$). Additional results are investigated to understand the biomechanical adaptations related to the anchoring technique, and better describe its interest for the fighters.

7.4 Ergonomics

Ergonomics has become an important application domain in MimeTIC: being able to capture, analyze, and model human performance at work. In this domain, key challenge consists in using limited equipment to capture the physical activity of workers in real conditions. Hence, in 2024, we have explored how simulation could help to support ergonomics in the specific case of interaction between a user and a physical system, such as a weelchair or an exoskeleton. We also explored how deep learning approaches could help to estimate biomechanical values from sparse and inaccurate human pose estimation.

7.4.1 Estimation of Upper-Limb Joint Torques in Static and Dynamic Phases for Lifting Tasks

Participants: Franck Multon *(contact)*, Charles Pontonnier, Georges Dumont, Hasnaa Ouadoudi Belabzioui.

Several systems propose to monitor the activity of workers in industry, with markerless Human Pose Estimation (HPE) methods based on deep learning. However, these systems simply provide sparse 3D human body keypoints, including noise and missing information. Hence, these sparse and noisy keypoints cannot be directly used to assess the biomechanical constraints associated with professional activity. Indeed, computing these constraints would require more accurate and high frequency motion capture data to compute reliable joint angles, or using inverse kinematics frameworks (such as OpenSim). Deep-learning (DL) based approaches, such as Opencap, have been introduced to estimate additional anatomical markers' positions, to overcome this limitation. However, such DL-based methods rely on training datasets and predefined keypoints and markersets, and their ability to generalize to other tasks or experimental conditions is still unclear. In this work, we assess the ability of Opencap, pre-trained with bipedal locomotion dataset, to generalize (i.e. estimate reliable 3D positions of additional anatomical markers) to bi-manual manipulation and picking tasks, and new markersets. Fine tuning, commonly used in DL to generalize a model to new data, is a promising mean to deal with unseen motions and different experimental conditions, with a few set of new training data. We evaluated the performance of various fine tuning strategies, such as retraining the full model, only the last layers or adding an additional output layer. Our results showed an important decrease of the estimation error when using fine tuning on picking and manipulation tasks, with new markersets, compared to directly applying the pretrained Opencap model. This decrease of error is obtained with a limited training dataset of 140,000 poses, which is promising for future use in new measurement conditions and unseen motions, as frequently observed in industry. Accurate Human Pose Estimation on-site is a key challenge to accurately assess musculoskeletal disorders with relevant and reliable biomechanical variables. However, RGB-based HPE used on-site generally provide sparse and noisy postural information, which is not compatible with standard biomechanical frameworks. This work suggests and evaluates guidelines to overcome this limitation, and to make standard HPE methods be used in biomechanical framework. This open new avenues in estimating biomechanical variables that could improve the estimation of the musculoskeletal disorders risks directly in industrial context, as it is performed in laboratory conditions. This work could be viewed as recommendations for companies which develop ergonomic assessment tools usable in industrial context.[19],[26].

7.4.2 Wheelchair locomotion ergonomics

Participants: Charles Pontonnier *(contact)*, Georges Dumont, Louise Demestre.

With regard to the objectives of the capacities project, we aimed at developing a synthetic costs of the physical demand in manual wheelchair locomotion. With regard to this objective, we made a first assessment in simulation of the biomechanical cost of slopes of increasing difficulty, using a wheelchair ergometer and a virtual simulator [23].

7.4.3 Stepping strategies for balance recovery in dense crowds

Participants: Charles Pontonnier *(contact)*.

This work has been mostly done in interaction with the Virtus research team [14]. The recovery strategies used by young adults to maintain standing balance following external forcecontrolled perturbations in densely populated group formations was investigated in this work. In particular, the moment of step initiation as well and the characteristics of the first recovery steps and hand-raising were studied here. The experimental data considered in this work are part of a larger dataset relying on a new experimental paradigm inspired by Feldmann and Adrian (2023). In this experiment, 20 participants (8 females, 12 males, 24.8 ± 3.7 yo) equipped with motion capture suits were asked to stand in tightly packed formation before receiving a force-controlled perturbation. In total, four group configurations and two interpersonal distancing conditions have been investigated here. The standing balance recovery strategies observed in this dense groups experiment were then compared with the observed behaviour of single individuals following external perturbations (Chatagnon et al., 2023). Results suggest that the moment of initiation for recovery steps was affected by the initial interpersonal distancing conditions. The first recovery steps within the studied dense groups were observed to be slower, smaller and more dispersed than those of single individuals for comparable level of perturbation intensity. However, the relationship between the average speed of first recovery steps and the length of these steps remained similar to the one of single individuals. This suggests that the first recovery step duration remained almost constant during both the dense groups experiment and the experiment with single individuals. Finally, we observed a significant occurrence of participants raising their hands, as physical interactions played an important role in this dense groups experiment. This behaviour was mainly observed to be initiated before recovery steps.

7.4.4 Backpack carriage effect on joint torques computed from a range of models: a preliminary study

Participants: Charles Pontonnier *(contact)*, Georges Dumont, Charles Pontonnier.

In a military framework, it could be interesting to predict biomechanical quantities such as joint torques and ground reaction forces while walking and carrying heavy loads. Indeed, these quantities could help to study injuries mechanism of low back pain or stress fractures related to the mass of the soldier's equipment carried on the field, which has nearly doubled since World War I. The aim of this study was to enhance motion analysis while carrying a backpack by developing a regression method able to provide information on the spine motion during walking. [31, 30, 21, 35].

7.5 Clinics

7.5.1 Force generation capacity mapping

The Inria Exploratory Action MusMapS uses effort measurements (mapping of physical capacities) from disabled patients to personalize the assistance of an upper-limb exoskeleton using shared control to help these patients with their everyday movements. The coupling of a musculoskeletal model representative of the patient's physical capabilities with a shared control system for pathologies such as multiple sclerosis or the after-effects of a stroke is innovative and forms the core of the approach. In the current work, we used pilot data to caracterize and modelize the force generation capacity at the elbow of two disabled people, one being subject to multiple sclerosis, one being subject to a stroke. The results showed lower capacities with regard to the reference, and different shapes that may come from many clinically defined differences [24].

8 Bilateral contracts and grants with industry

8.1 Bilateral contracts with industry

Cifre Moovency - Critère basé effort pour l'analyse in-situ de l'activité physique au travail : Application au port de charge bimanuel

Participants: Franck Multon *(contact)*, Georges Dumont, Charles Pontonnier, Hasnaa Ouadoudi Belabizoui.

This Cifre contract has started in January 2022 for three years and is funding the PhD thesis of Hasnaa Ouadoudi-Belabizoui. It consists in building robust AI-based methods able to emulate inverse dynamics results from noisy-incomplete data to study the physical constraints of the operators in industrial workplaces. Indeed, ergonomics of such workplaces need to be assessed at the effort level and no reliable method enables such an assessment in-situ from a motion monitoring. The thesis aims at developing neural networks able to reproduce the results of a model based inverse dynamics method and then at constructing a reliable and synthetic indicator of the forces undergone by the operator during the execution of a given task.

The Cifre contracts funds the PhD salary and 10K€ per year for the supervision and management of the PhD thesis.

Cifre InterDigitial - Deep interactive control of virtual character's motion based on separating identity, motion and style

Participants: Franck Multon *(contact)*, Adnane Boukhayma, Guillaume Loranchet.

This Cifre contract has started in November 2023 for three years and is funding the PhD thesis of Guillaume Loranchet. The aim of the project is to design stylized avatars of users in immersive environment, especially Metaverse applications.

This PhD position will focus on exploring, proposing and evaluating novel solutions to represent both body shape and movements in a compact latent representation. This representation aims at simplifying the adaptation of the shape (identity) of a user, or/and his motion, and/or the style of both his shape and motion (such as transferring the user's moving shape to a fictional character with different properties and style).

With the growing interest in persistent shared virtual worlds, such as the MetaVerse immersive social network, specific problems for character animation are raised. The objective of the PhD is to propose solutions to these problems. Indeed, in these environments, users are represented by avatars with different shapes and morphologies. Compared to the face, which has been studied for decades, there is no semantic controller for the body mesh, where one could easily change the motion type and style. The character animation platform should consequently be able to adapt the motion of the user to his/her specific shape (retargetting problem), or adapt the identity of the avatar so that the user is recognizable by his/her friends, or change the style of the motion to convey a given emotion or adapt to the expected behavior of the avatar. For example, a Hulk avatar is expected to move with a specific style, but should also mimic the characteristics of the user. Finally, the distribution of these avatar models over the network is a practical challenge due to the potential scale of the shared virtual worlds. Therefore, learning a representation that allows for efficient transmission and dynamic editing has a high practical impact.

The Cifre contracts funds the PhD salary and 15K€ per year for the supervision and management of the PhD thesis. This contract is also in collaboration with Hybrid team. The PhD has been defended in March 2022.

Cifre Technicolor - Face transformation and editing for digital visual effects in film production film production

Participants: Adnane Boukhayma *(contact)*, Kelianl Baert.

The aim of this thesis is to improve the controllability of learning-based techniques for editing photorealistic faces in video sequences, in the field of visual effects for cinema. The aim is to speed up post-production processes on faces by enabling an artist to finely control different characteristics (appearance, expression and face shape) over time: rejuvenation and aging, make-up/tattooing, strong modifications morphology (adding a 3rd eye, for example), replacing an understudy with the actor's face by the actor's face, adjustments to the actor's acting.

8.2 Bilateral grants with industry

Chaire SAFRAN-Fondation Saint Cyr: Le soldat augmenté dans l'espace numérique de bataille

Participants: Charles Pontonnier *(contact)*, Georges Dumont, Aurélien Schuster.

Led by Laurent Maheo (Full Professor, Ecoles de Saint-Cyr Coëtquidan). The Chair will focus on technical innovations at the level of the Félin infantry platoon. Research activities will focus on the human element, with the aim of improving the conditions under which infantrymen evolve in their environment, and addressing the following areas: protection of the soldier and his equipment, perception of the wealth of information coming back from sensors, collaborative data sharing, for which radio communications are a central issue, reducing cognitive load and strain, and increasing mobility. It involves a dozen research professors at the Saint-Cyr Coëtquidan schools. We take part in the Chair as a experts in physical activity analysis, and propose a research theme based on physical activity assistance (load-bearing assistance, mobility assistance). The Chair has been extended over the period 2023-2028, and our work has been extended by a new sponsorship thesis (Aurélien Schuster) on the energetic optimization of load-bearing through musculoskeletal modeling.

Swim power project

Participants: Nicolas Bideau *(contact)*, Guillaume Nicolas, Benoit Bideau, Yannis Raineteau.

The Swim Power project aims at evaluating the transfer of dryland strength and conditioning programs to optimize sprint swimming performance and should also provide new practical knowledge concerning improvements in the quality of this transfer. This grant (50% EUR Digisport, 50% French Swimming Federation) served to fund the PhD of Yannis Raineteau started in 2022.

SWIMO^{2p} project

Participants: Nicolas Bideau *(contact)*, Benoit Bideau, Antoine Bouvet.

The aim of SWIMO^{2p} is to develop a mono-sensor Inertial Measurement Unit (IMU) based tool for chronic monitoring of performance variables draw on human activity recognition (HAR) during swimming by neural network model. This grant (CDSN ENS Rennes) served to fund the PhD of Antoine Bouvet started in 2022.

Collaboration with INRS

Participants: Charles Pontonnier *(contact)*.

Since 2022, we collaborate with the Institut de Recherche en Sécurité et Prévention des Risques au Travail (INRS) through the co-supervision of a PhD student working on the physical evaluation of the impact of an upper-limb exoskeleton on a worker perfoming overhead work. In this work, we develop a complete analysis framework able to simulate the human-exoskeleton interaction with a detailed whole body musculoskeletal modele and a caractezised interface based on force and pressure measures at the arm and the pelvis. The framework will provide a detailed biomechanical analysis of the changes related to the exoskeleton with regard to the task and thus help the preventers to correctly use it and tune it for their operators.

9 Partnerships and cooperations

9.1 European initiatives

9.1.1 Horizon Europe

SHARESPACE

Participants: Franck Multon *(contact)*, Benoit Bideau, Richard Kulpa, Valentin Ramel, Julian Joseph.

SHARESPACE project on cordis.europa.eu

Title: Embodied Social Experiences in Hybrid Shared Spaces

Duration: From January 1, 2023 to December 31, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France

- ARS ELECTRONICA LINZ GMBH & CO KG, Austria
- ALE INTERNATIONAL, France
- UNIVERSITAT JAUME I DE CASTELLON (UJI), Spain
- CRDC NUOVE TECNOLOGIE PER LE ATTIVITA PRODUTTIVE SCARL (CRDC TECNOLOGIE SCARL), Italy
- RICOH INTERNATIONAL BV, Netherlands
- UNIVERSITE DE MONTPELLIER (UNIVERSITE DE MONTPELLIER), France
- GOLAEM SA (GOLAEM), France
- DE MONTFORT UNIVERSITY (DMU), United Kingdom
- DEUTSCHES FORSCHUNGSZENTRUM FUR KUNSTLICHE INTELLIGENZ GMBH (DFKI), Germany
- INSTITUT MINES-TELECOM, France
- UNIVERSITE RENNES II (RENNES 2), France
- UNIVERSITAETSKLINIKUM HAMBURG-EPPENDORF (UKE), Germany
- CYENS CENTRE OF EXCELLENCE (CYENS CoE), Cyprus
- SIA LIGHTSPACE TECHNOLOGIES, Latvia
- FUNDACIO HOSPITAL UNIVERSITARI VALL D'HEBRON - INSTITUT DE RECERCA (VHIR), Spain

Inria contact: Franck Multon

Coordinator:

Summary: SHARESHARESPACE will demonstrate a radically new technology for promoting ethical and social interaction in eXtended Reality (XR) Shared Hybrid Spaces (SHS), anchored in human sensorimotor communication. Our core concept is to identify and segment social sensorimotor primitives and reconstruct them in hybrid settings to build continuous, embodied, and rich human- avatar experiences. To achieve this, three interconnected science-towards-technology breakthroughs will be delivered: novel computational cognitive architectures, a unique self-calibrating body sensor network, and a fully mobile spatial Augmented Reality (AR) and virtual human rendering. We will create a library of social motion primitives and use them to design AI-based architectures of our artificial agents. SHARESPACE mobile capturing technologies combine loosely-coupled visual-inertial tracking of full body kinematic, hand pose and facial expression, incorporating novel neural encoding/decoding functionalities, together with local context-aware animations and highly realistic neural rendering. Our technology will be iteratively tested in 2 Proofs-of-principles involving human and artificial agents interacting in SHS, and 3 real-world use case scenarios in Health, Sport and Art. We will demonstrate a fully functional prototype of SHARESPACE tailored to the agents' personalized characteristics (gender, culture, and social dispositions). SHARESPACE will support community-building and exploitation with concrete initiatives, including (i) public engagement around our research and innovation, (ii) promoting high-tech innovation and early transfer to our deep-tech companies, as premises for the consolidation of human-centric and sovereign European market areas such Industry AR and SHS, eHealth and tele-Health. Our long-term vision is to bring XR to a radically new level of presence and sociality by reconstructing sensorimotor primitives that enable ethical, trusted and inclusive modes of social interaction.

9.2 National initiatives

ANR HoBiS

Participants: Franck Multon *(contact)*, Armel Cretual, Georges Dumont, Charles Pontonnier, Anthony Sorel, Benjamin Gamblin, Nils Hareng.

Hobis is a 42-month ANR collaborative (PRCI) project (2018-2024) entitled Hominin BipedalismS: Exploration of bipedal gaits in Hominins thanks to Specimen-Specific Functional Morphology. HoBis is leaded by the Museum Nationale d'Histoires Naturelles (CNRS), with CNRS/LAAS, and Antwerpen University (Belgium), with a total of 541KE budget (140KE for MimeTIC). HoBiS (Hominin BipedalismS) is a pluridisciplinary research project, fundamental in nature and centred on palaeoanthropological questions related to habitual bipedalism, one of the most striking features of the human lineage. Recent discoveries (up to 7 My) highlight an unexpected diversity of locomotor anatomies in Hominins that lead palaeoanthropologists to hypothesize that habitual bipedal locomotion took distinct shapes through our phylogenetic history. In early Hominins, this diversity could reveal a high degree of locomotor plasticity which favoured their evolutionary success in the changing environments of the late Miocene and Pliocene. Furthermore, one can hypothesize based on biomechanical theory that differences in gait characteristics, even slight, have impacted the energy balance of hominin species and thus their evolutionary success. However, given the fragmented nature of fossil specimens , previous morphometric and anatomo-functional approaches developed by biologists and palaeoanthropologists, do not allow the assessment of the biomechanical and energetic impacts of such subtle morphological differences, and the manners in which hominin species walked still remains unknown. To tackle this problem, HoBiS proposes as main objective a totally new specimen- specific approach in evolutionary anthropology named Specimen-Specific Functional Morphology: in- ferring plausible complete locomotor anatomies based on fossil remains, to link these reconstructed anatomies and corresponding musculoskeletal models (MSM) with plausible gaits using simulations. Both sub-objectives will make use of an extensive comparative anatomical and gait biomechanical data bases (challenges). To this end, we will integrate anatomical and functional studies, tools for anatomical modelling, optimization and simulation rooted in informatics, biomechanics, and robotics, to build an in-silico decision-support system (DSS). This DSS will provide biomechanical simulations and energetic estimations of the most plausible bipedal gaits for a variety of hominin species based on available re- mains, from partial to well-preserved specimens. MimeTIC is Leader of WP3 "Biomechanical simulation", aiming at predicting plausible bipedal lo- comotion based on paleoanthropological heuristics and a given MSM.

ANR CAPACITIES

Participants: Pontonnier Charles *(contact)*, Rouvier Théo.

CAPACITIES is a 48-month ANR project (2020-2024). This project is led by Christophe Sauret, from INI/CERAH. The objective here is to build a series of biomechanical indices characterizing the biomechanical difficulty for a wide range of urban environmental situations. These indices will rely on different biomechanical parameters such as proximity to joint limits, forces applied on the handrims, mechanical work, muscle and articular stresses, etc. The definition of a more comprehensive index, called Comprehensive BioMechanical (CBM) cost, including several of the previous indices, will also be a challenging objective. The results of this project would then be used in the first place in VALMOBILE application to assist MWC users in selecting optimal route in Valenciennes agglomeration (project founded by the French National Agency for Urban Renewal and the North Department of France). The MimeTIC team is involved on the musculoskeletal simulation issues and the biomechanical costs definition. The funding for the team is about 80kE.

PIA PPR Sport REVEA

Participants: Richard Kulpa *(contact)*, Benoit Bideau, Franck Multon, Guillaume Claude, Annabelle Limballe.

The REVEA project (2020-2025) proposes a new generation of innovative and complementary training methods and tools to increase the number of medals at the Paris 2024 Olympic Games, using virtual reality. Indeed, the latter offers standardization, reproducibility and control features that: 1) Densify and vary training for very high performance without increasing the associated physical loads, and by reducing the risk of impact and/or high intensity exercises ; 2) offer injured athletes the opportunity to continue training during their recovery period, or for all athletes during periods of confinement as experienced with Covid-19 ; 3) provide objective and quantified assessment of athlete performance and progress; and 4) provide a wide range of training that allows for better retention of learning and adaptability of athletes. Virtual reality offers a range of stimuli that go beyond the limits of reality, such as facing an opponent with extraordinary abilities or seeing an action that has not yet been mastered. The objective of REVEA is therefore to meet the needs of three federations by exploiting the unique properties of virtual reality to improve the motor performance of athletes through the optimisation of the underlying perceptual-motor and cognitive-motor processes. The French Gymnastics Federation wishes to optimise the movements of its gymnasts by observing their own motor production to avoid further increasing the load of physical training. The French Boxing Federation wishes to improve the perceptual-motor anticipation capacities of boxers in opposition situations while reducing the impact and therefore the risk of injury. The French Athletics Federation wishes to improve the perceptual-motor anticipation capacities of athletes in cooperative situations (4x100m relay) without running at high intensity. It is performed by a multidisciplinary consortium composed of University Rennes 2 (and Inria), University of Reims Champagne-Ardenne, Aix-Marseille University, Paris-Saclay University and INSEP.

PIA PPR Sport BEST Tennis

Participants: Benoit Bideau *(contact)*, Simon Ozan.

BEST-TENNIS (2020-2024) aims to optimize the performance of the service and return of service of the French Tennis Federation players (able-bodied and wheelchair) in the form of a systemic approach, capitalizing on biomechanical, clinical and cognitive data made available to coaches and athletes through dedicated tools. With its nine events at the Olympic and Paralympic Games, tennis is a sport with a high medal potential.

BEST-TENNIS is funded by the PIA3 PPR "Sport Haute Performance" call. This national project is leaded by researchers in MimeTIC.

PIA PPR Sport Neptune

Participants: Nicolas Bideau *(contact)*, Benoit Bideau, Guillaume Nicolas.

Swimming is a sport with a high medal potential at the Olympic and Paralympic Games. Winning can be decided in 1/100s: every detail of the performance must be evaluated with precision. This is the ambition of the NePTUNE project (2020-2024), with the support of the French Swimming Federation (FFN) and the Handisport Federation (FFH).

To meet the needs of these sports federations, the NePTUNE project focuses on three areas of work, in order to develop innovative methods and tools for coaches to monitor swimmers. A more advanced version on human movement and energetics as well as performance optimization will also be implemented, for more elaborate scientific measurements and research.

The first axis concerns the automatic tracking and race management strategies of swimmers in competition and in training race simulations, to support the performance of medallists, detect swimmers'talents and analyze the competition. Few swimming federations around the world are involved in this type of procedure, unlike the FFN, which is innovative with its semi-automatic tracking system. However, this system needs to be improved in order to offer a fully automatic and more accurate solution.

The second axis is interested in the study of motor coordinations, propulsion and energetics to understand how the transition of behavior takes place and how the frequency/amplitude ratio as well as the underwater part of the race can be optimized. Trainers need miniature and portable sensors (such as inertial units) that automatically and quickly provide key points of swimming technique in order to maximize effectiveness, efficiency and economy.

The third axis focuses on aquatic resistances and suction effect because high performance and economy are not only due to efficient propulsion but also to the minimization of passive and active resistances.

MimeTIC is partner of this PIA3 PPR Sport Haute Performance project, leaded by Université de Rouen Normandie.

PIA EUR Digidsport

Participants: Richard Kulpa *(contact)*, Benoit Bideau.

DIGISPORT (Digital Sport Sciences) (2020-2028) offers a comprehensive, hybrid graduate school encompassing the specialties in both sport and digital sciences. It provides excellence in research and teaching by serving both traditional students and industry professionals, as well as offering formal collaborations with regional research centers. DIGISPORT helps advance the use and efficacy of digital technologies in sports and exercise, impacting all stakeholders from the users, educators, clinical practitioners, managers, and actors in the socioeconomic world. From the master's to the doctoral level, the program aims to offer students in initial and continuing training an opportunity to build a study strategy suited to their professional goals and to the labor market. Students build their own learning path through a modular teaching offer, based on pedagogical innovation, hybridization of student populations and interdisciplinary projects. The high-level technological platforms are great training tools. DIGISPORT will host renowned international researchers for its teaching programs. The Rennes ecosystem is particularly well suited to host the DIGISPORT Graduate School, both in research and education and training. It incorporates world-class research units in the field of sport (top 300 in the Shanghai ranking), digital (top 100 in the Reuters ranking of the most innovative universities in Europe and top 300 medical technologies in the Shanghai ranking) but also electronics (top 200 for the Shanghai telecommunications ranking) and human and social sciences. The research units involved in DIGISPORT are affiliated with CNRS joint labs (IRISA, IETR, IRMAR, CREST), Inria teams, Grandes Ecoles network (ENS Rennes, INSA Rennes, CentraleSupelec, ENSAI) and Université de Rennes 1 and Université Rennes 2. Rennes is also a proven socioeconomic incubator with a large network of companies organized around the Images et Réseaux cluster, French Tech-Le Poool and prominent sport institutions (CROS, Campus Sport Bretagne).

9.2.1 Défi Ys.AI

Participants: Franck Multon *(contact)*, Ludovic Hoyet, Adnane Boukhayma, Tangui Marchand Guerniou, Guillaume Loranchet.

Ys.AI (2020-2026) is a joint project with InterDigital aiming at exploring the representation of avatars in Metaverse environments. More specifically, we aim at pushing the limits of the uncanny valley for highly realistic avatars. To this end, we explore how to enhance fullbody, garments and hair simulation using AI approaches. We also explore how these methods could enhance the interaction experience in immersive worlds, with multisensory feedback rendering.

9.2.2 PEPR eNSEMBLE

Participants: Franck Multon *(contact)*, Richard Kulpa, Anthony Sorel, Ahmed Abdourahman Mahamoud, Clelia Boulati.

eNSEMBLE (2023-2030) is an ambitious national project funded by the ANR PIA4 PEPR call. The eNSEMBLE project (Future of Digital Collaboration) aims to fundamentally redefine digital tools for collaboration. Whether it is to reduce the number of people on the move, improve territorial networking, or tackle the problems and transformations of the coming decades, the challenges of the 21st century will require collaboration at an unprecedented speed and scale.

For this to happen, a paradigm shift in the design of collaborative systems is needed, comparable to the one that saw the advent of personal computing. This means inventing shared digital spaces that do more than simply replicate the physical world in virtual environments, enabling co-located and/or geographically distributed teams to work together fluidly and efficiently.

In this context, MimeTIC is involved in the PhD thesis of Ahmed Abdourahman Mahamoud. The PhD topic consists in designing an AI-based controller of autonomous virtual humans that are supposed to behave as real human would do when interacting with users. More specifically, we explore imitation learning methods to train a controller to imitate the behavior of real humans in complex interaction tasks.

MimeTIC is also involved in the PhD thesis of Clélia Boulati, started in December 2024. This PhD thesis is performed in collaboration with Racing92 rugby pro club, in Paris. It aims at developping a method based on virtual environments and intelligent systems to optimise the performance of players involved in touch-throwing in rugby.

9.2.3 AeX MusMaps

Participants: Charles Pontonnier *(contact)*, Aurelie Tomezzoli, Mael Gallois.

The Inria Exploratory Action MusMapS (2024-2028) uses effort measurements (mapping of physical capacities) from disabled patients to personalize the assistance of an upper-limb exoskeleton using shared control to help these patients with their everyday movements. The coupling of a musculoskeletal model representative of the patient's physical capabilities with a shared control system for pathologies such as multiple sclerosis or the after-effects of a stroke is innovative and forms the core of the approach.

AAP CNRS Jumeaux numériques : Nouvelles frontières et futurs développements

Participants: Fougeron Nolwenn *(contact)*.

MITI is a 24-month project (2024-2025) This project is led by Yohan Payan (DR CNRS) from the TIMC laboratory. In collaboration with researchers from the Institut Pprime and the Muséum d'Histoire Naturelle, the objective is to create and evaluate digital twins of the lower limbs of bipeds in order to gain deeper understanding of the human and non human locomotion. The project is articulated around three main axes : imaging data collection, bench test validation of the models, analysis of evolutionnary differences between bipeds using digital twins. The first months have been dedicated to the second axis with the design a of multimodal bench test plateform for cadaveric samples and the settings of the first experiments. The pursuit of the bench tests experiments and the data collection will be the focus of the coming yeat. The funding for the project is about 30kE.

9.3 Public policy support

CORPS consortium management

Participants: Franck Multon *(contact)*.

CORPS is an unformal group created in 2024 in order to support the government for their policy to promote research and dissemination in sports and well being. The groups is composed of representatives of INSERM, INSEP, CNRS, C3D STAPS (sports science department coordination in French Universities), Agence Nationale du Sport (Ministery of sports), Ministery of Research, Paris hospitals APHP, Aix Marseille University, Science 2024 (Grande Ecole engineer schools). CORPS has produced documents which have been disseminated in Assemblé Nationale, Sénat and various French Ministeries, such as research, sports and economy. Franck Multon is leading the CORPS group, and is included in the future PEPR "Sport de Très Haute Performance2" core group, and is member of the GDR CNRS "Sport" steering committee.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Participants: Charles Pontonnier, Pierre Hellier, Franck Multon.

General chair, scientific chair

- Charles Pontonnier: Conference Chair of the Sports Physics Congress 2024 at the Inria Congress Center. The main objective of the Sports Physics conferences, which take place every Summer Olympic years since 2012, is to mix physics, mechanics, biomechanics, mathematics, computer sciences, data sciences and physiology to propose practical solutions to problems identified on field by coaches, medical teams and athletes. The attendees of the conference have different origins from fundamental and applied researchers to sport scientists, athletes and coaches in order to promote exchanges and collaborations. Since 2024 is special for France, this edition was also dedicated to the evaluation of the scientific impact of science in the Olympic results
- Franck Multon: co-organizer of the Next Generation Avatar NGA2025 workshop colocated with IEEE VR in Marche 2025. This workshop has been selected by the IEEE VR Workshop chairs.

Member of the organizing committees

- Pierre Hellier: organizer of special session *Implicit and Explicit Neural Representations for nD Video Compression* workshop at IEEE VCIP 2024.
- Franck Multon: IEEE VR2025 exhibitors and sponsorship co-chair.

Reviewer

- Franck Multon: reviewer for ACM Siggraph Asia, Pacific Graphics2024, and CASA conferences.

10.1.2 Journal

Participants: Charles Pontonnier, Georges Dumont.

Member of the editorial boards

- Charles Pontonnier: member of the EpiSciences "Multidisciplinary Biomechanics Journal" (Journal of the Société de Biomécanique) since 2024

Reviewer - reviewing activities

- Charles Pontonnier: Multidisciplinary Biomechanics Journal, Applied Ergonomics, Computer Methods in Biomechanics and Biomedical Engineering, Medical Engineering and Physics
- Georges Dumont : Multidisciplinary Biomechanics journal

10.1.3 Invited talks

Participants: Charles Pontonnier, Nicolas Bideau, Pierre Hellier, Richard Kulpa, Franck Multon.

- Franck Muton, invited talk, « Les défis de la réalité virtuelle pour comprendre et entraîner la performance sportive », colloque « Le mouvement humain des origines aux olympiades » Collège de France, 1-2 July 2024
- Charles Pontonnier, invited talk with Christophe Sauret (Institution des Invalides), "Biomécanique des interactions humain-système : du handicap au parasport", colloque "Handicap, sport et sciences du mouvement", Académie des Sciences, 1 October 2024
- Pierre Hellier, keynote talk " Learned image and video compression" at 36th International Conference on Scientific and Statistical Database Management, SSDBM 2024.
- Nicolas Bideau, invited talk, « Capteurs embarqués et IA au service de l'accompagnement scientifique de la haute performance sportive : Focus sur l'analyse de mouvements cycliques », colloque du GDR SOC^2 Systèmes embarqués et objets connectés, 11-13 June 2024
- Richard Kulpa, invited talk, "Réalité virtuelle pour améliorer la performance des boxeurs", Open Innovation Camp 2024, 14 Nov. 2024

10.1.4 Leadership within the scientific community

Participants: Georges Dumont, Nolwenn Fougeron, Franck Multon.

- Franck Multon is the coordinator of the "CORPS" group "Coordination des Organisations et Réseaux pour la Performance et les Sciences du sport" composed of INSERM, CNRS, C3D STAPS, MN-SHS, Sciences2024, INSEP, "Agence Nationale du Sport" (Ministery of sporrs), APHP, and MESRI (Ministery of research). This group aims at coordinating research in sports in multidisciplinary communities, and support the French government in decision-making in this domain.
- Franck Multon is member of the GDR CNRS "Sport" steering committee, since December 2024.
- Georges Dumont, Ronan Gaugne, Anthony Sorel, Richard Kulpa (and collegues) organized the Continuum Days (Equipex+) in Rennes with 60 participants.
- Nolwenn Fougeron: Member of the board of directors of the Société de Biomécanique.

10.1.5 Scientific expertise

- Franck Multon was reviewer for a national project submitted in the ANR AAPG call.

10.1.6 Research administration

Participants: Benoit Bideau, Armel Cretual, Georges Dumont, Richard Kulpa, Franck Multon.

- Franck Multon is responsible for the coordination of national Inria actions in Sports
- Franck Multon is the scientific representative of Inria in Sciences2024 group and scientific Committee

- Franck Multon is the scientific representative of Inria in the EUR Digisport steering committe and scientific committee
- Franck Multon is the co-director of the "Nemo.AI" joint Lab with InterDigital, and the associated Défi Ys.AI
- Armel Crétual is the elected head of the Sports Sciences departement (STAPS) in University Rennes2
- Benoit Bideau is the head of the M2S Laboratory
- Benoit Bideau is the leader of the EUR DIGISPORT project
- Charles Pontonnier is member of the EUR digisport pedagogical comitee
- Richard Kulpa is the co-leader of the EUR DIGISPORT project
- Richard Kulpa is the scientific head of the EUR DIGISPORT project
- Georges Dumont is part of EQUIPEX+ Continuum Project, head of this project for the four involved institutions from Rennes (ENS Rennes, INSA Rennes, University of Rennes, University of Rennes 2), co-leader of the scientific committee and of the executive committee
- Georges Dumont is member of the scientific commitee of EUR DIGISPORT project

10.2 Teaching - Supervision - Juries

- Master : Franck Multon, "Santé et Performance au Travail : étude de cas", leader of the module, 30H, Master 1 M2S, University Rennes2, France
- Master : Franck Multon, "Analyse Biomécanique de la Performance Motrice", leader of the module, 30H, Master 1 M2S, University Rennes2, France
- Master: Charles Pontonnier, "Lagrangian Mechanics", leader of the module, 16H, M2 Complex Systems Engineering, Ecole Normale Supérieure de Rennes, France
- Master: Charles Pontonnier, Research projects, 20H, M2 SIVOS, Ecole Normale Supérieure de Rennes, France
- Master: Charles Pontonnier, "Biomechanics Modeling", 15h, Ecole Normale Supérieure de Rennes, France
- Master: Charles Pontonnier, "Human-system Cosimulation", 20h, M2 SIVOS, Ecole Normale Supérieure de Rennes, France
- Master: Charles Pontonnier, "Mechatronic assistive devices", M2 SIVOS, 15h, Ecole Normale Supérieure de Rennes, France
- Master : Georges Dumont, Mechanical simulation in Virtual reality, 18H, Master Engineering of complex systems and Mechatronics, Rennes University and École Normale Supérieure de Rennes, France
- Master : Georges Dumont, Mechanics of deformable systems, 40H, Master, École Normale Supérieure de Rennes, France
- Master : Georges Dumont, oral preparation to agregation competitive exam, 20H, Master, École Normale Supérieure de Rennes, France
- Master : Georges Dumont, Vibrations in Mechanics, 10H, Master, École Normale Supérieure de Rennes, France
- Master : Georges Dumont, Finite Element method, 12H, Master, École Normale Supérieure de Rennes, France

- Master: Fabrice Lamarche, "Compilation pour l’image numérique", 29h, Master 1, ESIR, University of Rennes 1, France
- Master: Fabrice Lamarche, "Synthèse d’images", 12h, Master 1, ESIR, University of Rennes 1, France
- Master: Fabrice Lamarche, "Synthèse d’images avancée", 28h, Master 1, ESIR, University of Rennes 1, France
- Master: Fabrice Lamarche, "Modélisation Animation Rendu", 36h, Master 2, ISTIC, University of Rennes 1, France
- Master: Fabrice Lamarche, "Jeux vidéo", 26h, Master 2, ESIR, University of Rennes 1, France
- Master: Fabrice Lamarche, "Motion for Animation and Robotics", 9h, Master 2 SIF, ISTIC, University of Rennes 1, France.
- Master : Armel Crétual, "Méthodologie", leader of the module, 20H, Master 1 M2S, University Rennes2, France
- Master : Armel Crétual, "Biostatstiques", leader of the module, 30H, Master 2 M2S, University Rennes2, France
- Master : Richard Kulpa, "Boucle analyse-modélisation-simulation du mouvement", 27h, leader of the module, Master 2, Université Rennes 2, France
- Master : Richard Kulpa, "Méthodes numériques d’analyse du geste", 27h, leader of the module, Master 2, Université Rennes 2, France
- Master : Richard Kulpa, "Cinématique inverse", 3h, leader of the module, Master 2, Université Rennes 2, France
- Master: Pierre Hellier "Optimisation en machine learning", 10.5h, master IA, Université de Rennes, France.
- Licence : Franck Multon, "Ergonomie du poste de travail", Licence STAPS L2 & L3, University Rennes2, France
- Licence: Fabrice Lamarche, "Initiation à l’algorithmique et à la programmation", 56h, License 3, ESIR, University of Rennes 1, France
- License: Fabrice Lamarche, "Programmation en C++", 46h, License 3, ESIR, University of Rennes 1, France
- Licence: Fabrice Lamarche, "IMA", 24h, License 3, ENS Rennes, ISTIC, University of Rennes 1, France
- Licence : Armel Crétual, "Analyse cinématique du mouvement", 100H, Licence 1, University Rennes 2, France
- Licence : Richard Kulpa, "Biomécanique (dynamique en translation et rotation)", 48h, Licence 2, Université Rennes 2, France
- Licence : Richard Kulpa, "Méthodes numériques d’analyse du geste", 48h, Licence 3, Université Rennes 2, France
- Licence : Richard Kulpa, "Statistiques et informatique", 15h, Licence 3, Université Rennes 2, France
- Licence: Pierre Hellier, "introduction à l’IA", 36h, Licence 3, Université de Rennes, France.

10.2.1 Supervision

Participants: Adnane Boukhayma, Pierre Hellier, Georges Dumont, Charles Pontonnier, Franck Multon, Ronan Gaugne, Diane Haering, Richard Kulpa, Guillaume Nicolas, Nicolas Bideau, Anthony Sorel.

- PhD in progress (beginning May 2023): Amine Ouasfi: Self-supervised learning for implicit shape reconstruction. Adnane Boukhayma, Eric Marchand.
- PhD in progress (beginning November 2023): Antoine Dumoulin: Video-based dynamic garment representation and synthesis. Adnane Boukhayma, Pierre Hellier, stefanie wuhrer, Bharath Damodaran.
- PhD in progress (beginning August 2023): Kelian Baert: Transforming and editing faces for digital visual effects in film production. Adnane BOUKHAYMA, François BODIN, Marc CHRISTIE, Benoit MAUJEAN, Fabien CASTAN.
- PhD defended in December 2024 (beginning January 2022): Hasnaa Ouadoudi Belabzioui, Effort-based criterion for in-situ analysis of physical activity at work: application to load carrying, Charles Pontonnier, Franck Multon, Georges Dumont, Pierre Plantard (Moovency).
- PhD in progress (beginning June 2022): Shubhendu Jena, Combining implicit and explicit representations for modeling 3D Shape and appearance, Adnane Boukhayma, Franck Multon.
- PhD in progress (beginning November 2022): Sony Saint-Auret, Virtual Collaborative « Jeu de Paume », Ronan Gaugne, Valérie Gouranton, Franck Multon, Richard Kulpa.
- PhD defended December 2024 (beginning October 2021): Rebecca Crolan, Prediction of low back load during gymnastics landings for the prevention and follow-up of athlete injuries, Charles Pontonnier, Diane Haering, Matthieu Ménard (M2S Lab).
- PhD in progress (beginning November 2022): Etienne Ricard, Musculoskeletal modeling of the "human-exoskeleton" system, Charles Pontonnier, Chris Hayot, Kevin Desbrosses (INRS).
- PhD in progress (beginning November 2023): Guillaume Loranchet, Deep interactive control of virtual character's motion based on separating identity, motion and style, Franck Multon, Adnane Boukhayma, Pierre Hellier, François Shnitzler (InterDigital).
- PhD in progress (beginning December 2023): Ahmed Abdourahman Mahamoud, MAIL - AI-driven character simulation based on Multi-Agents Interaction Imitation Learning, Franck Multon, Richard Kulpa, Ewa Kijak and Simon Malinowski (LinkMedia team).
- PhD in progress (beginning May 2023): Valentin Ramel, Perception-Action Dynamics and synchronization in extented Reality Poloton cycling, Richard Kulpa, Benoit Bardy (Univ. Montpellier).
- PhD in progress (beginning October 2023): Aurélien Schuster, Musculoskeletal model of the infantryman: towards an energetic analysis of physical activity on mission for equipment and load optimization, Georges Dumont, Charles Pontonnier.
- PhD in progress (beginning october 2023) : Victor Restrat, Saut à la perche, analyse générique du mouvement humain et des techniques d'interaction (PAOLI: Pole Vault generic analysis, human motion and optimal interaction), Ecole normale supérieure, Georges Dumont, Nicolas Bideau, Guillaume Nicolas
- PhD in progress (beginning November 2024) : Célélia Boulati, Analyse des coordinations spatio-temporelles en sport collectif pour la modélisation comportementale en environnement virtuel : application à la touche au rugby, Université de Rennes, Franck Multon, Nicolas Vignais, Anthony Sorel

- PhD in progress (beginning september 2023) : Suzon Pucheu, Quantification des impacts de réception sur agrès en gymnastique à partir de méthodes de localisation de d'estimation de la source, ENS Rennes, Charles Pontonnier, Diane Haering, Mathieu Aucejo (CNAM Paris)
- PhD defended May 2024 (beginning December 2020): Mohamed Younes, Apprentissage et Simulation des Stratégies de Sport (la Boxe) pour l'Entrainement en Réalité Virtuelle, Franck Multon, Richard Kulpa, Ewa Kijak (IRISA/Linkmedia), Simon Malinowski (IRISA/Linkmedia).
- PhD in progress (beginning september 2023) : Florian Matéos, Biofidélité de l'interaction pied-ballon en réalité virtuelle au service de l'évaluation et l'optimisation de la prise de décision au football, ENS Rennes, Richard Kulpa, Anthony Sorel
- PhD in progress (beginning september 2022) : Simon Ozan, Validation and exploitation of a markerless motion capture system to analyze and optimize "in-situ" the serve biomechanics of high level tennis, ENS Rennes, Richard Kulpa, Caroline Martin
- PhD in progress (beginning september 2024) : Louis Arlés, Comprendre et optimiser l'action des membres inférieurs dans le cadre du service au tennis : analyse des déterminants biomécaniques et des liens avec la performance et les risques de blessures, ENS Rennes, Richard Kulpa, Caroline Martin
- PhD in progress (beginning october 2022) : Antoine Bouvet, Monitoring and Modeling of Performance in Swimming via Inertial Sensor and Data Science - Methodologies and Applications for Scientific Support to Performance, Nicolas Bideau, Mathieu Marbac-Lourdelle (ENSAI) via Centrale Inertielle et Data Science
- PhD in progress (beginning october 2024): Kilian Bertholon, AQUATIC (Advanced Quantitative Underwater Tracking and Inertial Capture): An IMU-based approach for in situ 3D motion capture and biomechanical evaluation covering all swimming strokes, Nicolas Bideau, Benoit Bideau
- PhD in progress (beginning october 2023) : Nolwenn Regnault, Entrainement perceptif chez le cavalier pour l'optimisation des interactions cavalier-cheval en saut d'obstacles, Nicolas Bideau, Benoit Bideau, Agnès Olivier (IFCE)

10.2.2 Juries

Participants: Pierre Hellier, Georges Dumont, Charles Pontonnier, Richard Kulpa, Franck Multon, Laurent Guillo.

- PhD defense: Univ. Rennes, Yann Moullec, "Multisensory feedback to enhance the simulation of walking in virtual reality for rehabilitation", December 2024, Franck Multon, president
- PhD defense: Univ. Rennes, Yuliya Patotskaya, "Engaging Motion : Exploring the Impact of Dynamic Properties of Virtual Humans on User Perception", December 2024, Franck Multon, president
- PhD defense: Univ. Toulon, Bilal Ghader, "Amélioration des interaction drone plongeurs (AMDIP)", November 2024, Franck Multon, examiner
- PhD defense: Centrale Supelec, Guénolé Fiche, "Learned Latent Representations for Human Mesh Recovery", November 2024, Franck Multon, president
- PhD defense: Centrale Supelec, Glenn Kerbiriou, "Data-driven Eye Region Reconstruction, Modeling and Animation", June 2024, Franck Multon, president
- PhD defense: University of Liverpool, Flávia Alves, "Human Activity Recognition using Smart Home Sensors and Motion Capture Data", May 2024, Franck Multon, examiner

- PhD defense: Université de Université Paris-Est Créteil, Mohamed Adjel, "Toward the development of a sparse, multi-modal and affordable motion analysis system. Applications to clinical motor tests", May 2024, Charles Pontonnier, rapporteur
- PhD defense: Université de Université Paris Saclay, Inoussa Ouedraogo, "Immersive Analytics Collaborative sur des données météorologiques et climatologiques", October 2024, Charles Pontonnier, rapporteur
- PhD defense: Université de Montréal, Amédéo Céglia, "Développement et validation d'un estimateur en temps réel des forces musculaires et articulaires pour la réadaptation du membre supérieur combinant commande optimale et vision informatique", December 2024, Charles Pontonnier, examinateur externe (rapporteur)
- PhD defense: Université de Bordeaux, Gautier Laisné, "Upper-limb force feasible set: theoretical foundations and musculoskeletal model reconstruction", December 2024, Charles Pontonnier, rapporteur
- PhD defense: Université Grenoble Alpes, Clément DLUZNIEWSKI, "Télé-Immersion 3D basée sur des Caméras 360° et des Casques de Réalité Étendue", September 2024, Georges Dumont, Président
- PhD defense: UNIVERSITE CLAUDE BERNARD LYON 1, Anaïs CHAUMEIL, "Évaluation et développement de méthodes d'analyse du mouvement sans marqueurs à partir de vidéos", November 2024, Georges Dumont, Rapporteur
- PhD defense: IPP Paris, Gwilherm Lesné, "Édition d'Attributs d'Images et Rendu de Grain Argentique à l'aide de Réseaux de Neurones Profonds", Pierre Hellier, examiner
- PhD defense: Université Bretagne Sud, Mansour TCHENEGNON, "3D motion reconstruction with deep learning methods - Application to motor disabilities", November 2024, Richard Kulpa, President
- Civil servant recruitment jury: Laurent Guillo took part as a member of the jury in the selection of a research engineer for INRIA in Lyon, June 2024.
- Civil servant recruitment jury: Laurent Guillo took part as a member of the jury in the selection of a research engineer and an assistant engineer for the rectorate of the Rennes academy, september 2024.

10.3 Popularization

Participants: Franck Multon.

- numerous journalist papers for the wide public audience, in the specific context of Olympic Games Paris2024: Sciences & Avenir, L'Express, Le Parisien, Ouest France, Les Numériques, Blog du Modérateur, Radio France, France Info Sport, etc.

10.3.1 Productions (articles, videos, podcasts, serious games, ...)

Participants: Franck Multon.

- co-production with the Inria communication department of a series of podcasts about the Inria research projects applied to sports and especially Olympic Games.

10.3.2 Participation in Live events

Participants: Benoit Bideau, Franck Multon.

- Coordination of a booth at the JOP Paris 2024-Club France, hosted on the MESRI (Ministry of Higher Education, Research and Innovation) space, Grande Hall de La Villette, on the occasion of the Paris 2024 Olympic Games, 26/07-11/08/2024. Demonstrations of the European ShareSpace project (Virtual Reality to improve cycling performance). 1500 participants tested the demo, and 500 agreed to give up their data for large-scale experimentation. MESRI figures show that 15,000 visitors came to the stand over the 15-day period.
- Franck Multon was Inria ambassador and participated in the Inria booth dedicated to sport, for the Fête de la Science, October 5-6, 2024, at the Musée de l'Homme. Demonstrations of the PPR "REVEA" project, interview with "Esprit Sorcier".
- Coordination of the Inria booth at the Fête de la Science in Rennes, October 13-15, with the same demonstration.
- Co-organizer with Rennes Metropole of the "Sport Unlimitech" event in Rennes on March 26, 2024, bringing together leading academic, industrial and sporting players to develop new technologies for sport (10 conferences and round tables, 26 exhibitors).

11 Scientific production

11.1 Major publications

[1] A. Bouvet, R. Pla, E. Delhaye, G. Nicolas and N. Bideau. 'Profiling biomechanical abilities during sprint front-crawl swimming using IMU and functional clustering of variabilities'. In: *Sports Biomechanics* (18th June 2024), pp. 1–21. DOI: 10.1080/14763141.2024.2368064. URL: https://inria.hal.science/hal-04632780.

[2] D. S. Chander, A. Tomezzoli, M. P. Cavatorta, M. Gréau, S. Marie and C. Pontonnier. 'Biomechanical requirements of meat cutting tasks: a pilot study quantifying tasks sustainability and assistance required at the wrist'. In: *Applied Ergonomics* 116 (2023), pp. 1–41. DOI: 10.1016/j.apergo.2023.104186. URL: https://inria.hal.science/hal-04272926.

[3] E. Delhaye, A. Bouvet, G. Nicolas, J. P. Vilas-Boas, B. Bideau and N. Bideau. 'Automatic Swimming Activity Recognition and Lap Time Assessment Based on a Single IMU: A Deep Learning Approach'. In: *Sensors* 22.15 (2022), p. 5786. DOI: 10.3390/s22155786. URL: https://hal.science/hal-03775394.

[4] L. Demestre, S. Grange, C. Dubois, N. Bideau, G. Nicolas, C. Pontonnier and G. Dumont. 'Characterization of the dynamic behavior of a diving board using motion capture data'. In: *Sports Engineering* (2022), pp. 1–18. URL: https://hal.inria.fr/hal-03788858.

[5] A. Limballe, R. Kulpa and S. Bennett. 'Using Blur for Perceptual Investigation and Training in Sport? A Clear Picture of the Evidence and Implications for Future Research'. In: *Frontiers in Psychology* 12 (2nd Mar. 2022). DOI: 10.3389/fpsyg.2021.752582. URL: https://hal.inria.fr/hal-03656204.

[6] P. Morin, A. Muller, G. Dumont and C. Pontonnier. 'Comparison of two contact detection methods for ground reaction forces and moment estimation during sidestep cuts, runs and walks'. In: *Journal of Biomechanical Engineering* 146.1 (2024), pp. 1–9. DOI: 10.1115/1.4064034. URL: https://inria.hal.science/hal-04256186.

[7] N. Olivier, G. Kerbiriou, F. Argelaguet Sanz, Q. Avril, F. Danieau, P. Guillotel, L. Hoyet and F. Multon. 'Study on Automatic 3D Facial Caricaturization: From Rules to Deep Learning'. In: *Frontiers in Virtual Reality* 2 (19th Jan. 2022), pp. 1–15. DOI: 10.3389/frvir.2021.785104. URL: https://hal.inria.fr/hal-03763591.

[8] H. Ouadoudi Belabzioui, C. Pontonnier, G. Dumont, P. Plantard and F. Multon. 'Generalization of Inverse Kinematics Frameworks Based on Deep Learning to New Motor Tasks and Markersets'. In: *International Journal of Industrial Ergonomics* (2024), pp. 1–22. URL: https://inria.hal.science/hal-04808920.

[9] A. Vu, A. Sorel, A. Limballe, B. Bideau and R. Kulpa. 'Multiple Players Tracking in Virtual Reality: Influence of Soccer Specific Trajectories and Relationship With Gaze Activity'. In: *Frontiers in Psychology* 13 (20th May 2022), pp. 1–14. DOI: 10.3389/fpsyg.2022.901438. URL: https://hal.inria.fr/hal-03674770.

[10] X. Wang, A. Boukhayma, S. Prévost, E. Desjardin, C. Loscos and F. Multon. 'Coupling dense point cloud correspondence and template model fitting for 3D human pose and shape reconstruction from a single depth image'. In: International Conference on Interactive Media, Smart Systems and Emerging Technologies (IMET). Limassol, Cyprus, 2022, pp. 1–8. URL: https://hal.inria.fr/hal-03830670.

[11] M. Younes, E. Kijak, R. Kulpa, S. Malinowski and F. Multon. 'MAAIP: Multi-Agent Adversarial Interaction Priors for imitation from fighting demonstrations for physics-based characters'. In: *Proceedings of the ACM on Computer Graphics and Interactive Techniques* 6.3 (16th Aug. 2023), pp. 1–20. DOI: 10.1145/3606926. URL: https://hal.science/hal-04136868.

11.2 Publications of the year

International journals

[12] A. Bilhaut, A.-H. Olivier, J. Draper Rodi, A. Cretual and M. Ménard. 'Assessing the effects of manual therapy on pain in patients living with persistent non-specific low back pain (PNSLBP): Which evaluation criteria and measurement tools are used in randomised controlled clinical trials? A systematic review'. In: *International Journal of Osteopathic Medicine* 55 (Mar. 2025), p. 100741. DOI: 10.1016/j.ijosm.2024.100741. URL: https://hal.science/hal-04888248.

[13] A. Bouvet, R. Pla, E. Delhaye, G. Nicolas and N. Bideau. 'Profiling biomechanical abilities during sprint front-crawl swimming using IMU and functional clustering of variabilities'. In: *Sports Biomechanics* (18th June 2024), pp. 1–21. DOI: 10.1080/14763141.2024.2368064. URL: https://inria.hal.science/hal-04632780 (cit. on p. 20).

[14] T. Chatagnon, S. Feldmann, J. Adrian, A.-H. Olivier, C. Pontonnier, L. Hoyet and J. Pettré. 'Standing Balance Recovery Strategies of Young Adults in a Densely Populated Environment Following External Perturbations'. In: *Safety Science* (2024), pp. 1–21. URL: https://inria.hal.science/hal-04620504 (cit. on p. 22).

[15] A. Limballe, R. Kulpa, E. Verhulst, S. Ledouit and S. J. Bennett. 'Virtual reality boxing: impact of gaze-contingent blur on elite boxers performance and gaze behavior'. In: *Frontiers in Sports and Active Living* 6 (2024), p. 1430719. DOI: 10.3389/fspor.2024.1430719. URL: https://hal.science/hal-04876947 (cit. on p. 19).

[16] W. Mocaër, E. Anquetil and R. Kulpa. 'Early gesture detection in untrimmed streams: A controlled CTC approach for reliable decision-making'. In: *Pattern Recognition* (June 2024), p. 110733. DOI: 10.1016/j.patcog.2024.110733. URL: https://hal.science/hal-04634678 (cit. on p. 19).

[17] G. Montagne, N. Mascret, M. Bossard, L. Chomienne, S. Ledouit, G. Rao, N. Tordi, E. Verhulst and R. Kulpa. 'An interdisciplinary framework to optimize the anticipation skills of high-level athletes using virtual reality'. In: *Frontiers in Sports and Active Living*. Frontiers in Sports and Active Living 6 (2024), p. 1324016. DOI: 10.3389/fspor.2024.1324016. URL: https://hal.science/hal-04479743 (cit. on p. 18).

[18] P. Morin, A. Muller, G. Dumont and C. Pontonnier. 'Comparison of two contact detection methods for ground reaction forces and moment estimation during sidestep cuts, runs and walks'. In: *Journal of Biomechanical Engineering* 146.1 (2024), pp. 1–9. DOI: 10.1115/1.4064034. URL: https://inria.hal.science/hal-04256186 (cit. on p. 17).

[19] H. Ouadoudi Belabzioui, C. Pontonnier, G. Dumont, P. Plantard and F. Multon. 'Generalization of Inverse Kinematics Frameworks Based on Deep Learning to New Motor Tasks and Markersets'. In: *International Journal of Industrial Ergonomics* (2024), pp. 1–22. URL: https://inria.hal.science/hal-04808920 (cit. on p. 22).

[20] Y. Raineteau, R. Pla, B. Bideau, N. Bideau and G. Nicolas. 'From dry-land to the water: training and testing practices of strength and conditioning coaches in high level French sprint swimmers'. In: *Frontiers in Sports and Active Living* 5 (12th Jan. 2024), p. 1338856. DOI: 10.3389/fspor.2023.1338856. URL: https://hal.science/hal-04415386 (cit. on p. 20).

International peer-reviewed conferences

[21] M. Amouroux, X. Wang, C. Pontonnier and A. Tomezzoli. 'Comparison of two alignment methods prior to principal component analysis, for vertebra positions prediction from cutaneous markers'. In: *Multidisciplinary Biomechanics Journal*. 2024 - 49ème congrès de la société de biomécanique. Compiègne, France: EPIsciences, 2024, pp. 1–2. URL: https://inria.hal.science/hal-04727211 (cit. on p. 23).

[22] R. Crolan, R. Bidet, F. Dal Maso, M. Ménard, C. Pontonnier and D. Haering. 'Kinematic and muscular strategies of the lower back during backward somersault landing in gymnastics'. In: *ISBS Proceedings Archive*. ISBS 2024 - International Society of Biomechanics in Sports Congress. Salzburg, Austria, 2024, pp. 1–4. URL: https://inria.hal.science/hal-04537937 (cit. on p. 21).

[23] L. Demestre, A. A. Ghezala, T. Rouvier, T. Poulain, G. Conreur, J. Bascou, H. Pillet, C. Sentouh, C. Pontonnier and C. Sauret. 'Analyse biomécanique de la propulsion en fauteuil roulant manuel lors de la locomotion sur des pentes dans un environnement simulé'. In: *Actes de la Conférence Handicap*. Conférence Handicap 2024. Paris, France, 2024. URL: https://inria.hal.science/hal-04550571 (cit. on p. 22).

[24] E. Larribau, A. Tomezzoli, B. Cassard, M. Babel, E. Leblong and C. Pontonnier. 'Elbow force generation capacities evaluation of post-stroke and multiple sclerosis patients: a pilot study'. In: *Multidisciplinary Biomechanics Journal*. 2024 - 49ème congrès de la société de biomécanique. Compiègne, France: EPIsciences, 2024, pp. 1–3. URL: https://inria.hal.science/hal-04727187 (cit. on p. 23).

[25] F. Le Failler, O. Massoutier, C. Pontonnier and F. Multon. 'Comparison of two Qwan ki do punching techniques'. In: 2024 - Sport Physics conference. Rennes, France, 2024, pp. 1–1. URL: https://inria.hal.science/hal-04826686 (cit. on p. 21).

[26] H. Ouadoudi Belabzioui, C. Pontonnier, G. Dumont, P. Plantard and F. Multon. 'Generalization of Marker Augmenter Learning Models on a New Motion Database for Inverse Kinematics'. In: *Multidisciplinary Biomechanics Journal*. 2024 - 49ème congrès de la société de biomécanique. Compiègne, France: EPIsciences, 2024, pp. 1–2. URL: https://inria.hal.science/hal-04727199 (cit. on p. 22).

[27] A. Ouasfi and A. Boukhayma. 'Unsupervised Occupancy Learning from Sparse Point Cloud'. In: CVPR 2024 - IEEE/CVF Conference on Computer Vision and Pattern Recognition. Vol. 34. Seattle, United States, 2024, pp. 21729–21739. DOI: 10.1109/cvpr52733.2024.02053. URL: https://hal.science/hal-04720091 (cit. on p. 18).

[28] S. Pucheu, D. Haering, M. Aucejo and C. Pontonnier. 'First analysis of gymnastics landing load prediction using LSTM neural network based on acceleration data'. In: 2024 - Sport Physics conference. Rennes, France, 2024, pp. 1–1. URL: https://inria.hal.science/hal-04826671 (cit. on p. 21).

[29] V. Restrat, N. Bideau, G. Nicolas, J. Cassirame and G. Dumont. 'Energy assessment during pole vaulting using inertial motion capture: a preliminary study'. In: *Multidisciplinary Biomechanics Journal*. 2024 - 49ème Congrès de la Société de Biomécanique. Compiègne, France: EPIsciences, 2024, pp. 1–3. URL: https://enpc.hal.science/hal-04738214 (cit. on p. 19).

[30] A. Schuster, C. Pontonnier and G. Dumont. 'Evaluating the use of IMUs to study obstacle crossing kinematics in situ'. In: 2024 - Sport Physics conference. Rennes, France, 2024, pp. 1–1. URL: https://inria.hal.science/hal-04826694 (cit. on p. 23).

[31] A. Schuster, C. Pontonnier and G. Dumont. 'Kinematic reconstruction of the spine with a regression model for load carriage study among soldiers'. In: *Multidisciplinary Biomechanics Journal*. 2024 - 49ème congrès de la société de biomécanique. Compiègne, France: EPIsciences, 2024, pp. 1–2. URL: https://inria.hal.science/hal-04727192 (cit. on p. 23).

Conferences without proceedings

[32] A. Bouvet, G. Nicolas and N. Bideau. 'Profiling pacing and underlying kinematics during 400m front-crawl with embedded sensors and functional modeling of large database: highlighting the technical regulations of various performance level'. In: ECSS 2024 - Annual Congress of the European College of Sport Science. Glasgow (Ecosse), United Kingdom, 2024, pp. 1–1. URL: https://inria.hal.science/hal-04633625 (cit. on p. 20).

[33] M. Egiziano, L. Chomienne, M. Bossard, E. Verhulst, R. Kulpa, N. Mascret and G. Montagne. 'How variability could shape perceptual-motor expertise in 4x100 m relay?' In: ECSS 2023 - Annual Congress of the European College of Sport Science. Paris, France, 2024, pp. 1–1. URL: https://amu.hal.science/hal-04469325 (cit. on p. 18).

[34] V. Restrat, N. Bideau, A. Marin, G. Nicolas and G. Dumont. 'Bending energy in pole vaulting using motion capture and Kirchhoff-Cosserat's rod theory'. In: Sport Physics 2024. Rennes, France, 3rd Dec. 2024. URL: https://hal.science/hal-04872717 (cit. on p. 19).

Reports & preprints

[35] A. Tomezzoli, A. Naaïm, B. Fréchède and S. Duprey. *An alternative thorax coordinate system for motion analysis in sitting postures, applicable to both sexes*. 2024. URL: https://hal.science/hal-04737936 (cit. on p. 23).