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FROM SENSORS TO BIOFEEDBACK AND EXOSKELETONS: HOW BIOMECHANICS MAY SUPPORT ERGONOMICS

Habilitation à Diriger des Recherches

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par

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Avant-propos

L'écriture et la soutenance d'un mémoire d'HDR représente une étape structurelle dans une carrière de chercheur : il pose un regard sur les travaux menés dans le passé, pour mieux se projeter vers les projets à venir. Ce travail d'équilibriste fournit l'occasion de revenir sur le chemin parcouru à travers les cinq grandes phases qui ont jalonné ma carrière de chercheur.

La première fut l'**Université Rennes 2** où je découvris le monde de la recherche entre 2000 à 2010. Rapidement au cours de mon cursus en STAPS, les sciences du mouvement humain prirent une place importante, notamment à travers les cours de Biomécanique. Cet intérêt m'amena à postuler au laboratoire Mouvement, Sport, Santé (M2S) pour un stage en 3ème année de Licence. A force d'insister, un ancien doctorant, Briac Colobert, accepta de m'encadrer, en collaboration avec deux étudiantes de Master 1. Et ce fut le début de l'aventure... Un autre enseignant-chercheur, Armel Crétual, certainement fatigué par mes relances incessantes, consentit à superviser mon travail de Master 1. Une année plus tard, Benoit Bideau, un jeune docteur du laboratoire, se mit à la recherche d'un étudiant pour continuer son travail de thèse sur l'analyse du mouvement du gardien de but de handball en environnement virtuel. C'est dans cette lignée que s'inscrivirent mes travaux de thèse pluridisciplinaires, en collaboration avec Richard Kulpa, Pr. Paul Delamarche et Benoit Bideau, alors tout juste promu Maitre de Conférences au laboratoire M2S. Cette équipe dynamique me permit d'appréhender l'analyse du mouvement humain dans une situation sportive, avec l'aide de la technologie (ici la Réalité Virtuelle). Au-delà de la biomécanique, ce fut aussi une première expérience passionnante avec la boucle "Perception-Action", boucle qui reviendra sous différentes formes au cours de ce mémoire.

Au cours de ces années passées au sein du laboratoire M2S, je sentis qu'un domaine m'attirait particulièrement : celui de l'ergonomie physique. Cette discipline peut en effet être investiguée avec les mêmes méthodes que celles de la biomécanique du mouvement sportif, mais pour des finalités plus appliquées, comme la prévention des troubles musculo-squelettiques. J'eus alors l'opportunité d'intégrer l'**Université de Technologie de Compiègne** sous la supervision bienveillante du Pr. Frédéric Marin (2010-2012). Au sein du projet européen COGNITO, les interactions avec les collègues anglais, allemands et portugais furent très riches (bien que certaines réunions, en anglais, me parurent parfois difficiles...). Je découvris une autre façon de mener des travaux de recherche, et l'importance du calendrier pour mener à bien un projet de recherche. Par le développement d'un modèle musculo-squelettique de la main et de l'avant-bras, je fus au coeur de la simulation biomécanique, avec son lot d'hypothèses mécaniques sous-jacentes. Etrangement, j'ajoutai à ces développements biomécaniques des questions de contrôle moteur : nous proposâmes avec l'aide de mes collègues allemands Markus Miezal et Gabriele Bleser, d'utiliser un score ergonomique en temps-réel pour faciliter le mouvement des travailleurs pendant la réalisation de tâches manuelles

industrielles. La boucle (*sic*) et la technologie (ici la Réalité Augmentée) revenaient une fois de plus me hanter...

Ces deux années furent un tremplin idéal pour continuer mes recherches à l'international. Et c'est ainsi que le laboratoire de biomécanique occupationnelle de l'**Université McMaster** (Ontario, Canada) et le Pr. Peter Keir m'accueillirent pour deux années remarquables (2012-2014). Evoluant dans un nouvel environnement, confrontant mes méthodes et mes raisonnements, supervisant des recherches et des étudiants au quotidien, cette période me permit clairement de gagner en autonomie et d'asseoir une vision "collaborative" des sciences du mouvement humain. Grâce aux études de terrain, combinées à la validation de modèles en laboratoire, le champ de l'ergonomie physique s'ouvrit en grand. Et cela renforça l'idée qu'il était possible d'innover méthodologiquement, en menant des évaluations ergonomiques objectives sur le terrain, grâce aux nouvelles technologies, notamment par l'intermédiaire de différents capteurs embarqués. Avec la miniaturisation des outils d'analyse, la période était propice ! Curieusement, c'est à la fin de cette parenthèse canadienne que j'obtins une bourse de recherche pour comparer la réalisation de tâches manuelles en environnements réel et virtuel, la boucle me poursuivait...

De retour an France, j'exerçai en tant que chargé d'enseignement et de recherche à l'**Université de Technologie de Belfort-Montbéliard** pendant une année, dans l'équipe ERCOS dirigée par le Pr. Jean-Claude Sagot (2014-2015). Je bénéficiai alors d'un environnement de recherche avec de multiples outils d'analyse et de nombreux contacts professionnels. C'est notamment à cette période que j'entrevis la possibilité de coordonner "demande d'une entreprise" et "questionnement scientifique". Autrement dit comment la démarche scientifique trouve sa place sur le terrain, dans un environnement socio-prefessionnel, pour le bien-être de la société. D'un point de vue méthodologique, cette année consolida l'idée qu'il était possible d'analyser tout type de mouvement professionnel. Les échanges avec les collaborateurs industriels firent également germer les premières réflexions sur l'apport d'une assistance physique pour faciliter le mouvement humain au travail.

Depuis 2015, en tant que Maitre de Conférences à la Faculté des Sciences du Sport de l'**Université Paris-Saclay**, j'ai la chance de pouvoir appliquer ces différentes approches à travers mes recherches. A la fois fondamentales lorsqu'il s'agit de comprendre comment l'humain s'adapte à un exosquelette, mais aussi appliquées pour réaliser des évaluations ergonomiques et sportives en continu à partir de capteurs embarqués, ces recherches sont toujours menées en collaboration avec des collègues investis et passionnés. La boucle "Perception-Action" est bien présente, à travers l'utilisation de retours sensoriels en temps réel, contribuant ainsi à optimiser le mouvement humain, c'est-à-dire faciliter son exécution tout en prévenant l'apparition de blessures. Ces différentes approches peuvent être englobées dans un modèle conceptuel d'ergonomie physique au service de la prévention des troubles musculo-squelettiques, modèle qui sera présenté dans ce mémoire.

Ce document est organisé en deux grandes parties. La première constitue la synthèse de mes travaux de recherche, projets et activités, ainsi qu'une projection sur les études à venir. La deuxième intègre une sélection d'articles publiés. Dans la première section, trois chapitres sont présentés :

Le premier chapitre synthétise mes principaux travaux de recherche réalisés jusqu'à présent, en s'appuyant sur le contexte initial des troubles musculo-squelettiques, véritable enjeu de santé publique. A partir d'un modèle conceptuel de l'ergonomie physique en cinq étapes (modélisation, capteurs, analyse, évaluation, intervention), mes recherches se déclinent en trois sous-parties : (i) l'évaluation ergonomique à partir de capteurs embarqués, (ii) l'utilisation de retour sensoriel temps-réel, *i.e. biofeedback*, pour l'amélioration du mouvement humain, et (iii) l'analyse des interactions homme-exosquelette.

Dans un second chapitre, mes projets de recherche à venir sont exposés, avec pour objectif d'approfondir les cinq étapes du modèle conceptuel de l'ergonomie physique. Ces différentes étapes feront l'objet de propositions de recherches futures et/ou en cours. La question de la mesure, sous différentes formes, sera abordée. Il sera également question de l'application de ce modèle au service de la performance sportive, en collaboration avec des partenaires privés. L'intérêt des exosquelettes passifs au service de la prévention des troubles musculo-squelettiques sera souligné. Enfin, de nouvelles pistes pour le contrôle intuitif d'un exosquelette actif de membre supérieur seront présentées.

Pour finir, le troisième chapitre résume mes différentes activités académiques, que ce soit les publications issues des études, les enseignements effectués ainsi que les responsabilités académiques.

NOTA BENE : il a été décidé de rédiger ce manuscrit en langue anglaise pour plusieurs raisons. La première concerne le fait qu'une partie de ces écrits est/sera soumise dans des journaux internationaux. La seconde raison est liée à la réutilisation future de ces écrits pour répondre à des appels à projets nationaux ou internationaux. Enfin, on entend trop souvent que peu de personnes prennent le temps de lire une HDR. J'ai l'humble ambition d'élargir le lectorat en passant par la langue anglaise...

Remerciements

Voilà un exercice tout aussi difficile que celui d'écrire une HDR : remercier les personnes qui ont participé, de près ou de loin, à la conduite et la réussite des projets de recherche présentés dans ce document. Je tâcherai d'être exhaustif et succinct, tel un funambule maintenant l'équilibre entre sphères professionnelle et personnelle...

Tout d'abord, je remercie mes rapporteur(e)s et examinateurs/trice d'avoir accepté de faire partie de mon jury d'HDR. C'est un réel plaisir d'avoir pu compter sur vous pour l'aboutissement de ce travail.

Mon parcours professionnel m'aidera certainement à n'oublier personne pour la suite (et si c'est le cas, je m'en excuse !). Ainsi je commencerai par remercier mes amis et collègues rennais qui me suivent depuis toujours : Anthony, Anne-Hélène, Armel, Antoine, Frédéric, Richard. Un merci tout particulier à Benoit Bideau qui a accepté de faire partie de ce jury, et qui m'a transmis une certaine vision (dynamique et active !) de l'enseignement et de la recherche, vision que je cherche aujourd'hui à partager à mon tour. Ma formation scientifique me mena ensuite à Compiègne où je fis des rencontres très enrichissantes qui perdurent aujourd'hui... Merci à Jean-Sébastien et Charlotte, à Laetitia, à Quentin, mes meilleurs partenaires de raid ! Merci également à Markus et Gabi, mes supers collègues allemands. Un remerciement spécial à Frédéric Marin qui a lui aussi accepté de participer à ce jury, et qui a clairement sa part dans mon parcours scientifique... avoir une approche globale d'un questionnement scientifique, en intégrant différents acteurs et partenaires... voilà une petite partie de ce que j'ai pu apprendre à tes côtés... et promis je continuerai à mettre des chemises en conférence ! Vint ensuite le temps du Canada, au rythme des saisons et du climat... Ce fut la découverte d'une université, la McMaster University, et de citoyens chaleureux, les ontariens. Un grand merci à John et Andréa, tout comme Mike et Debra, pour leur inestimable amitié. Je remercie également Peter Keir qui m'a accueilli à la McMaster University et qui m'a appris la juste valeur des choses en recherche. Je découvris ensuite la Franche-Comté et l'Université de Technologie de Belfort-Montbéliard. Même si mon séjour fut court là-bas (1 an), je tiens à remercier Jean-Claude Sagot pour son accueil et sa vision, Fabien, Morgane et les autres pour les moments partagés. Enfin j'ai débarqué à Orsay il y a 7 ans... Université Paris-Sud puis Université Paris-Saclay, c'est un environnement en perpétuel mouvement... et tellement accueuillant ! Je commencerai par remercier l'équipe des doctorants du laboratoire CIAMS, pour leur bonne humeur et leur répartie. Ils sont la dynamique actuelle et à venir de la recherche, ne l'oublions pas. Un merci tout particulier à mes doctorants passés (Alexander, Benjamin, Simon) et actuels (Lucas, Alexandre, Thomas, Kevin, Matthieu) avec qui j'ai pris et je prends plaisir à travailler. Un énorme merci à mes collègues et amis de la Faculté des Sciences du Sport qui contribuent au sourire que je porte le matin en arrivant, qu'elles/ils soient enseignants-chercheurs (Caroline, Carole, Alexandra, Marie, Anne, Samuel,

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Vient ensuite le moment de remercier les amis et les proches, qui participent par les moments partagés, à cet équilibre entre vie personnelle et vie professionnelle. Merci à mes amis limouriens pour tous ces bons moments : Florence, Elodie, Cédric et Matthieu. Merci à la filière franco-autrichienne pour cette si belle amitié : Céline, Norbert et leurs enfants. Merci à Caro et Thomas, vendeur de tapis exceptionnel mais ami avant tout. Merci à mes amis de longue date qui suivent tout cela de près ou de loin, et qui aiment tellement entendre parler d'exosquelette en soirée : Nico, Ronny et Elo, Jojo et Marie, Yann et Ingrid, Yvan et Justine, Norbert, Matthieu, Jéjé et Charlotte, Yoann, Hélène et Jozic, Jérèm et Rozenn, Kris et Sandrine, Steph et Steph, Sophy, Loïc, Cathy.

Enfin, il est temps je crois de souligner le rôle que joue la famille dans ce parcours. Que ce soit au moment de la formation lorsque j'étais étudiant, ou par ce suivi régulier qui m'a remis en question et donné l'envie d'entreprendre, ma famille a toujours été un soutien sans faille. Merci à mes frères, Maxime et Mathieu, mes belles-soeurs, Emilie et Virginie, et mes neveux et nièces, Maé, Nino, Lisa, Violette, Eden, Yuna et Jade. Merci à mes parents, Chantal et Serge, vous êtes des modèles de valeurs que je ne cesserai de vouloir transmettre. Merci à mes enfants, Azélie et Eliott, je vous aime... vous qui me permettez tous les jours de relativiser sur les subtilités de mon métier ;)

”Un croyant, c’est un antiseptique”

Raymond Devos,

Les Antipodes, 1976

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List of abbreviations

MSDs	musculoskeletal disorders
DOF	degree of freedom
EMG	electromyography
IMU	inertial measurement units
RULA	rapid upper limb assessment
CTS	carpal tunnel syndrome
CTP	carpal tunnel pressure
DHM	digital human model
HMD	head mounted display
LOD	level of details
COM	center of mass
RMS	root mean square
CP	cerebral palsy
MMG	mechanomyography
HEI	human-exoskeleton interaction
CG	compensation of gravity
GRF	ground reaction forces
EEG	electroencephalography

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2.1 Research objectives of the 1st axis into the physical ergonomics framework. MMG sensors will be compared to EMG sensors, and analyzed through time and frequency domains, for isometric (MVC) and dynamic muscle contractions. These results will permit to define a MMG-based methodology for ergonomic assessment. . . 80

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2.4 Research objectives of the 4th axis into the physical ergonomics framework. In addition to kinematics, EEG and high density (HD) EMG sensors will be used to feed a neuromusculoskeletal (NMS) model of the upper limb. This model will permit to relate muscle activity to joint torques. Real-time integration of these commands (reduced-to-complete muscle models) will be assessed through the measurement of transparency into HEI. These data will be also used to improve the corresponding neuromusculoskeletal model (*e.g.* calibration process). 85

Part I

Research and academic activities

In this part of the manuscript, I firstly present a summary of my past works and confront them to a physical ergonomics model of human movement in Chapter 1. Secondly I outline future studies and research project related to this approach for the coming years in Chapter 2. In Chapter 3, a full CV of my academic activities is finally described.

Chapter 1

1 Synthesis of previous works

THIS chapter presents a research framework dedicated to the prevention of musculoskeletal disorders (MSDs) during occupational activities, which is a central issue in ergonomics. According to the International Ergonomics Association, ergonomics (or human factors) may be defined as the scientific discipline concerned with the understanding of interactions between humans and the other elements of a system, and the profession that applies theory, principles, data, and methods to design, in order to optimize human well-being and overall system performance (IEA, 2016). Ergonomics is derived from the Greek *ergon* (work) and *nomos* (laws). Being both a science and a profession, ergonomics is formed by three broad domains of specialization:

- Cognitive ergonomics, concerned with mental processes such as perception, decision-making, memory, mental workload, as they influence interactions among humans and other elements of a system.
- Organizational ergonomics (or macroergonmics), dedicated to the design of work systems and organization-system interactions with the aim to examine ways to optimize entire workplaces.
- Physical ergonomics, focused on human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity in occupational environments. Overall approaches to physical ergonomic interventions work best to reduce the incidence of work-related MSDs (Dennerlein, 2008, January 1).

Beginning by an introduction about definition and facts related to MSDs, this chapter then presents different strategies for preventing MSDs from a physical ergonomic perspective. The first strategy is related to the identification of MSDs risk factors by computing ergonomic scores through embedded sensors worn by the worker. This ergonomic analysis step permits to recommend solutions in order to redesign workplaces *a posteriori*. Using outcomes of an ergonomic score

through feedbacks given to the worker in real-time may represent a second innovative strategy. An example of this biofeedback methodology is also given in a motor readaptation context. A last strategy is proposed by assisting workers physically during forceful exertions. With this in mind, exoskeletons are introduced, representing a promising solution for MSDs prevention.

1.1 Musculoskeletal disorders: a critical public health issue

Work-related MSDs is a damage that affects the musculoskeletal system of the human body, especially at bones, spinal discs, tendons, joints, ligaments, cartilage, nerve, and blood vessels (NIOSH, 1997). MSDs can occur in all parts of the body, although the back, neck, shoulders and upper limbs are the most commonly affected areas. When MSDs are primarily caused or aggravated by work and the work environment, they are called work-related MSDs. Main MSDs related to professional acitivties are carpal tunnel syndrome, tendinitis (at wrist, elbow, shoulder, or knee level), rotator cuff injuries affecting the shoulder, epicondylitis affecting the elbow, and low back injuries (muscles strain and sprain). MSDs have a significant incidence on the worldwide professional sector, this component is presented in the first part of this contextual introduction. Such injuries mainly result from physical demands (*e.g.* repetitive motions, lifting tasks, forces, and vibrations), but psychosocial factors (*e.g.* work stress) also need to be considered into prevention strategies. Symptoms associated to MSDs may be observed at workplaces when there is an offset between the human physical capacity and the physical requirements of the occupational task (Korhan and Memon, 2019), the so called *physical risk factors*. These factors are exposed in the second part of this section.

1.1.1 Quantitative impact for workers and society

Before introducing numbers about MSDs, it is necessary to distinguish work-related accident, *i.e.* a sudden event that creates a personal injury, from professional disease, *i.e.* a long-term affection due to occupational activities. In France, four out of five professional diseases are nowadays MSDs (INRS, 2020b). Joints of the upper limbs are particularly at risk, with shoulder, elbow and wrist/hand representing 30%, 22% and 38% of all MSDs, respectively. Although low back MSDs account for 7% of body parts affected by MSDs, they stand for 20% of all work-related accidents, and 30% of six months' leaves from work in 2016. Direct costs of MSDs for companies are estimated at 2 billions of euros in 2017. It has to be noted that women are significantly more impacted by work-related MSDs than men (55% vs 45%, respectively) in France (INRS, 2020b).

At global level, approximately 640 workers suffer from work-related accidents and four workers

die of an industrial accident or occupational disease in each minute according to the International Labour Organization (Chan and Man, 2022). Across all the European Union member states, MSDs are the leading cause of work disability, sickness absence from work, 'presenteeism' and loss of productivity. They affect at least 100 million people in Europe, with back pain accounting for the highest proportion of years lost to disability of all conditions, with neck pain and other MSDs all in the top ten ranking. From a public health perspective, MSDs represent 40% of the cost of worker compensation in some European Union countries (Eurofound, 2012). This may lead to a reduction of 1 to 2% in the gross domestic product of individual member states (Bevan, 2015). And this observation is continuously increasing: in USA, costs associated to MSDs would have risen from 3.4% to 5.8% of the gross domestic product over the last 18 years (USBJI, 2020). This is confirmed by worldwide reported rates of MSDs, which increased from 54.2% to 60.1% between 2007 and 2013 across the European Union for example (Eurofound, 2017). Physical risk factors associated to MSDs also follow this inclination.

1.1.2 Physical risk factors associated to MSDs

Work-related MSDs may be caused by different (combination of) risk factors like sociodemographic, individual, environmental, organisational, psychosocial and physical factors. The main cause of work-related MSDs appear to be physical risk factors (HSE, 2021), with a drastic rise over last years, especially for repetitive hand and arm movements (see Figure 1.1).

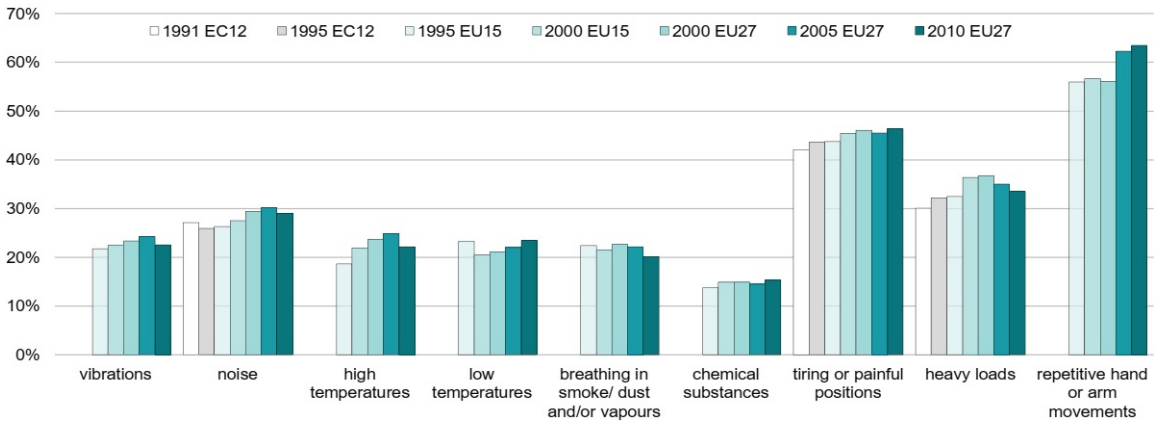


Figure 1.1: Exposure to physical risks over time (% exposed quarter of time or more) (based on Eurofound, 2012).

Previous studies from the literature have found reasonable evidence for an association between MSDs and the following physical risk factors:

- posture
- working in awkward positions
- heavy physical work
- lifting
- repetitive work
- prolonged computer work

More precisely, previous epidemiological studies provided strong evidence of a biomechanical pathway between physical work exposures and the increased risk of work-related MSDs (Bernhard, 1997; Keyserling et al., 1992; Marras et al., 1995; Punnett et al., 1991). The cumulative trauma model provides one explanation for the occupational relevance of MSDs specifically due to repeated and long durations of external load handling and/or forceful exertions performed throughout the workday (Radwin, Marras, et al., 2001). This model posits that injury results from the accumulated effect of transient external loads that, in isolation, may be not exceed internal tissue tolerances. Exposures from repetitive and/or prolonged duration cause cumulative microdamage such as the internal tolerances of tissues are eventually exceeded.

Prevalence of MSDs in Europe is associated with working in tiring or painful positions, carrying or moving heavy loads, and repetitive hand or arm movements (EASHW, 2019). This applies to MSDs related to back, upper limbs and lower limbs. In addition, it has to be noted that being exposed to vibrations from hand tools also increases the probability of reporting any of these three types of MSDs. Finally, it should not be forgotten that there is a link between MSDs and mental health, with a growing evidence that the combination of these two conditions is a significant factor inhibiting early return to work (Alavi et al., 2016).

1.1.3 Prevention strategies for work-related MSDs

Work and work environment are causing or aggravating MSDs. Different strategies can thus be settled to prevent MSDs, ranging from technical and engineering measures, over more organisational approaches, to person-oriented interventions. The European Union legislation mentions that prevention of work-related MSDs has to be based on a *risk assessment* process while respecting general principles of prevention, *e.g.* avoiding the risks, evaluating the risks which cannot be avoided, combating the risks at source, adapting the work to the individual, adapting to technical

progress, etc. (EU, 1989, June 12). More generally, work-related MSDs appearance may be prevented with different strategies, that may be categorized in three levels of prevention (EASHW, 2008; EASHW, 2022, January 12):

- **Primary prevention** includes the risk assessment process, and technical/ergonomic, organisational and person-oriented interventions
  - *Risk assessment process*: may be considered as the basis for the prevention of MSDs at work. As a primary prevention measure, *i.e.* avoiding the occurrence of a disorder by reducing or avoiding risk factors, ergonomic risk assessment is the systematic examination of all aspects of work, considering and evaluating the work-related and individual exposure of workers to physical and psychosocial risk factors. In support of the risk assessment, several methods may be used (see section 1.1.4). The risk assessment process allows to identify prevention priorities. Risk assessment can also be applied as a secondary prevention measure, *i.e.* early recognition of disorders and halting their progression, by identifying workers at risk, ensuring the systematic monitoring of their health and investigate work-related causal factors. This should allow early intervention actions and prevent acute MSDs become chronic.
  - *Technical/ergonomic intervention*: aims to reduce the physical workload and thus decrease the risk for MSDs. These interventions can amongst others focus on the elimination or reduction of risks related to manual handling of loads, working in awkward postures, repetitive work and hand-arm tasks, etc. To this aim, different technical interventions may be proposed: automation or mechanisation, ergonomic workplace redesign, introduction or redesign of ergonomic work equipment and tools, use of exoskeletons (see section 1.4) and protective equipment.
  - *Organisational interventions*: this concerns a broad range of measures related to the work organisation in order to improve the psychosocial work environment. It may include the distribution of work tasks, job design, work processes, work pace, management style, working time, etc. Examples of organisational interventions include changing staffing levels, adapting work cycle frequencies, changes to the frequency/duration of breaks, or adapting work tasks.
  - *Person-oriented interventions*: these strategies refer to education, *i.e.* ergonomic-related guidance and training programmes, in order to change their working behaviour. Physical exercises may also be considered as person-oriented interventions. The objective is to increase the worker's physical capacity and thus reduce the discrepancy between the workload and the capacity of the worker (Korhan and Memon, 2019).
- **Secondary prevention**, involves the identification and health monitoring of workers at risks.

- **Tertiary prevention**, comprises return-to-work actions.

1.1.4 Risk factors assessment methodologies

Different methods and tools have been developed for assessing exposure to risk factors for work-related MSDs. These methods can be classified in three groups: self-reports, observational methods and direct measurements (David, 2005; Li and Buckle, 1999). Self reports involve worker diaries, interviews and questionnaires. Despite their ease of implementation, self-reports have been associated with subjective drawbacks like the unreliability of exposure perception or interpretation according to the worker's literacy.

The aim of observational methods is to evaluate workplace exposure by assessing the worker's motor behavior on paper sheets either while observing in the field or replaying videos (Engstrom and Medbo, 1997). A non-exhaustive list of them includes Quick Exposure Check, Manual Tasks Risk Assessment tool, Rapid Entire Body Assessment, Loading on the Upper Body Assessment, Hand Activity Level-Threshold Limit Value, Ovako Working posture Assessment System, Occupational Repetitive Actions, Strain Index, Snook Tables and the National Institute for Occupational Safety and Health lifting equation (Andreoni et al., 2009). One of the most cited observational methods is the Rapid Upper Limb Assessment (RULA) method, which is based on postures observation (biomechanical and postural load parameters) to provide a score of exposure to MSDs, with particular attention to the neck, trunk and upper limbs (McAtamney and Corlett, 1993). Thus this method estimates the exposure to upper limb MSDs by computing a global risk score. It is one of the most cited method in the ergonomic literature (Gomez-Galan et al., 2020) which has been frequently applied in industry (Lowe et al., 2019). Reliability of the RULA method adapted to specific contexts has been assessed through different studies (Dockrell et al., 2012; Levanon et al., 2014; Takala et al., 2010). For a current posture, the global RULA score ranges from one to seven, one being most comfortable. This score is based on upper-body posture, muscle use, weight of lifted loads, task duration, and repetitiveness (see Figure 1.2).

Observational methods have also been implemented into videotaped specific softwares (Chan and Man, 2022; Radwin, 2011; Yen and Radwin, 1995) even though this process was usually time-consuming. More simply, videotaping is a standard tool in ergonomics as it permits to divide a work cycle in different key elements, denoted as subtasks (Hernandez-Arellano et al., 2016). The amount of time spent during each of these subtasks can also be deduced as a percentage of the work cycle (Armstrong et al., 2014). Although observational methods are affordable and practical for use in a wide range of professional situations, the scoring system may suffer from a lack of epidemiological data (David, 2005; Li and Buckle, 1999).

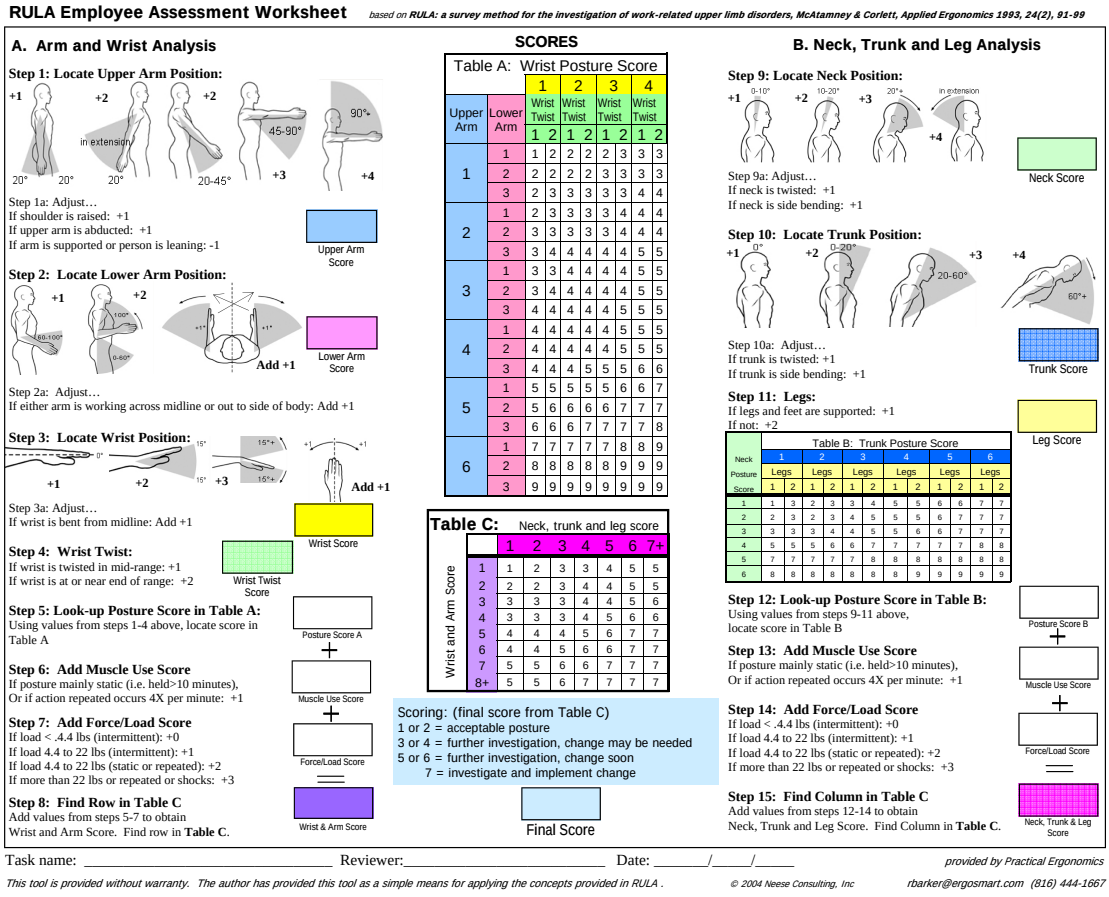


Figure 1.2: RULA table (adapted from McAtamney and Corlett (1993)).

Finally, direct measurement methods allow for measuring the risk of exposure for long duration, and are considered advantageous in terms of performance (*e.g.* accuracy, precision) and cost (Lim and D'Souza, 2020). However, portability and wearability of direct instrumentation is vital to minimize potential interference with worker movements and work performance. Examples of direct instrumentation used for field measurement of the risk of exposure include electrogoniometers (Radwin and Lin, 1993) and inclinometers (Bernmark and Wiktorin, 2002; Hansson et al., 2001). Examples of force measurement instrumentation in situ are pressure mapping insoles (Forner Cordero et al., 2004), instrumented force shoes (Faber et al., 2010), instrumented gloves (Castro and Cliquet, 1997), and electromyography (EMG) for estimating the magnitude of force exertion from muscle activity (Theado et al., 2007). Although this kind of methods have been known to

require complex implementation and cost-intensive hardware setup (David, 2005), low-cost and intuitive systems based on electrogoniometers and inertial measurement units (IMU) have been introduced by manufacturers, *e.g.* XSens (Netherlands), Trigno, Delsys (USA), CAPTIV Motion, TEA (France).

As set out in the European Union legislation, prevention of work-related MSDs should be based on the process of risk assessment, which is defined as the process of evaluating risks to workers' safety and health from workplace hazards. From a physical ergonomics perspective, an ergonomic intervention aims at detecting and evaluating the disequilibrium between workplace requirements and workers physical abilities. Therefore, developing supportive tools for the identification and assessment of potentially hazardous motor tasks and postures appears crucial for ergonomic research.

1.1.5 A conceptual ergonomics-based framework using on-body sensors

Preventive efforts to lessen the work-related MSD impact encountered limited success, conducting researchers to develop new frameworks for work-related MSDs prevention research. This effort aims at better linking relevant research disciplines (*e.g.* epidemiology, biomechanics, applied physiology) into a single ergonomic prevention strategy (van der Beek et al., 2017). Concurrently, advances have been made in these disciplines thanks to wearable sensing technologies. Indeed, miniaturized, wireless, body-worn inertial sensors offer opportunities to directly measure vast and personalized biomechanical data in both laboratory and applied settings, which may be of prime interest for the assessment of physical risk factors (Stefana et al., 2021). Recently, a conceptual ergonomics-based framework has been proposed by Lim and D'Souza (2020) to englobe the contemporary uses of inertial sensing in ergonomics research: the Modeling-Sensing-Analysis-Assessment-Intervention framework (see Figure 1.3). This model permitted to describe the typical role of wearable inertial sensing and sensor data for biomechanical exposure assessment.

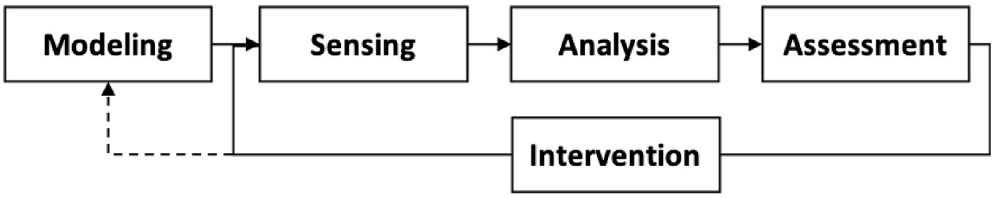


Figure 1.3: Conceptual framework for biomechanical exposure assessment using wearable inertial sensors spanning Modeling, Sensing, Analysis, Assessment, and Intervention. The dotted line indicates that the modeling component can be updated based on comparisons between the expected and actual behavior (Lim and D'Souza, 2020).

The different steps composing the model may be detailed as follow:

- *Biomechanical modeling* precedes the use of inertial sensing as it represents the relationships between critical elements of the 'worker-equipment-task' system. This modeling step both includes very explicit form of modeling, *e.g.* musculoskeletal modeling or finite element modeling, and implicit kinematics assumptions, *e.g.* joint angles obtained from inertial measurement units (IMUs).
- *Sensing* considers the types of sensors and measurement variables appropriate for a particular task analysis, the locations for sensor attachment, and the process of measuring worker postures and movements. As an example, a biomechanical model of the upper body may be supported with IMUs placed on the worker's trunk, head, upper arms, forearms and hands.
- The *analysis* component refers to the different approaches selected to process data. It may not only concern predictive techniques (*e.g.* machine learning) to obtain measures of specific biomechanical exposures but also descriptive or inferential statistics. Certain exposure characteristics such as force exertions, loads handled or subtask-related exposure, are often not directly available from inertial sensor data, hence additional methods (*e.g.* direct observation, indirect video-based observations, direct measurement, or work diaries) get used in conjunction with body-worn inertial sensing.
- *Assessing* implies that the quantified exposures are either compared to previously established "absolute" limits and thresholds to assess physical workload and/or risk of MSDs (*e.g.* NIOSH Lifting Index, RULA or OWAS scores) or compared in "relative" terms (*e.g.* comparisons between different occupations, task conditions, used tools, pre- vs. post-intervention).
- On the basis of these elements, *interventions* may be prioritized and decided. It may be actions that will modify work content in order to reduce the risk of work-related MSDs, increase task performance, and/or improve worker well-being (see section 1.1.3).

The closed feedback loop in this conceptual framework indicates that the biomechanical exposures may be assessed across time (*i.e.* longitudinally, or pre- and post-intervention), or compared between conditions (*i.e.* cross-sectional designs). Finally, the modeling component can be updated based on comparisons between the expected (*i.e.* modelled or hypothesized) and actual (*i.e.* measured or observed) behavior of the system.

On the basis of this model, the methodology proposed in this manuscript aims to prevent MSDs by: (i) using simple-to-complex model of the upper-body, (ii) selecting a panel of appropriate on-body sensors to record biomechanical parameters, (iii) analyzing these parameters to statistically

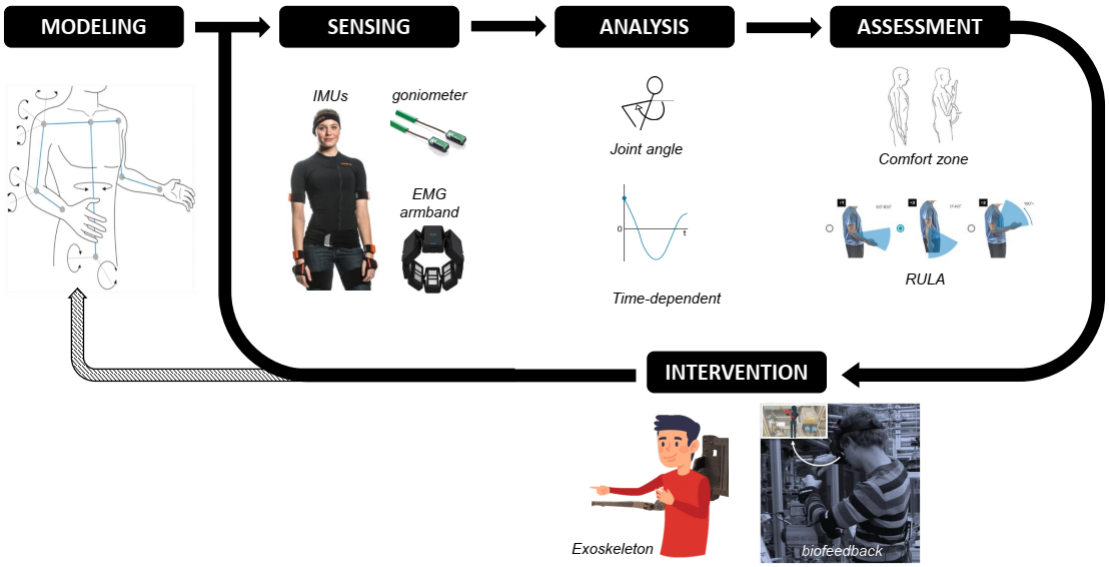


Figure 1.4: Proposed approach for prevention of MSDs based on ergonomic exposure assessment using on-body sensors. The shaded arrow indicates that biomechanical modeling may be updated based on comparisons between the expected and actual behavior (inspired from Lim and D'Souza (2020)).

test relevant indices of biomechanical exposures, (iv) comparing obtained values with relative or reference limits and thresholds, and (v) acting on the workplace to reduce the work-related MSDs and by evaluating the impact of these modifications (closed-feedback loop). It will be also possible to directly update the model through real-time feedback. The first advantage of this approach comes from the fact that ergonomic scores may be computed *continuously*, *i.e.* a score is not only calculated for one frame but for all frames of an occupational task. Upstream of the ergonomic intervention, this temporal feature of the ergonomic assessment allows a comprehensive analysis of the professional activity for risk factors identification (see Figure 1.4, first four steps). Different types of this analysis will be presented in the next section (section 1.2), with on-body sensors located at different anatomical positions, *i.e.* from one joint to multiple articulations, with single or combined sensors, and for different application fields (logistical, artisanal and industrial areas). Wireless wearable on-body sensors are also affording opportunities to use ergonomic assessment in real-time, thus suggesting direct feedback strategies in the workplace (see Figure 1.4). The modality of a visual biofeedback for real-time applications will be presented in a second section (section 1.3). Finally, an ergonomic intervention framework based on exoskeletons will be introduced (section 1.4).

1.2 An ergonomic assessment methodology based on on-body sensors

When studying routine or cyclical work, biomechanical exposures are typically measured by sampling work to estimate either all or a subset of the three main exposure dimensions (*i.e.* intensity, repetition, and duration). These estimates are usually extrapolated to a longer time period (*e.g.* workday or shift) to quantify the cumulative biomechanical exposure (Lim and D'Souza, 2020). However, non-repetitive jobs may be defined as jobs that display variation and diversity in terms of work element frequency, duration, or content (Gold et al., 2006; Mathiassen, 2006). In such cases, exposure assessment performed on a small sample of workers or using discrete-interval work sampling may not capture the work-relevant exposures and MSD risk (Paquet et al., 2005), suggesting the work assessment may need to be done across multiple workers over long work periods. Accurate, reliable and cost-effective quantification of biomechanical exposures in these types of occupational activity provides the underlying motivation for this section.

1.2.1 Ergonomic assessment based on electrogoniometers

1.2.1.1 Development of a carpal tunnel risk model

Electrogoniometers may firstly be used to focus on the assessment of a specific joint like the wrist, as this articulation is subject to one of the most known MSD: the Carpal Tunnel Syndrome (CTS). CTS represents the most common peripheral neuropathy, affecting the median nerve at the wrist (Vignais, Weresch, et al., 2016). There is strong support for biomechanical factors like posture, repetition, force and duration for the development of CTS in the forearm and wrist (NIOSH, 1997; Steven Moore, 2002). Proposed mechanisms specific to CTS include: (i) increased pressure within the carpal tunnel, and (ii) compression of the median nerve with friction or tethering of the median nerve. Each of these mechanisms is affected by force and posture. Empirical evidence demonstrates that wrist extension increases the pressure in the carpal tunnel, while wrist flexion leads to impingement on the median nerve (Keir, Wells, et al., 1997). Moreover, it has been showed that even a light pinch grip increases the curvature of the tendon paths through the carpal tunnel, acting to increase the compressive force experienced by the median nerve (Keir and Wells, 1999; Smith et al., 1977). Thus, guidelines for posture based on pressures have been created (Keir, Bach, et al., 2007) but, to date, a workplace assessment tool or model capable of predicting CTS risk does not exist. However, data currently exist to develop a model predicting: (i) carpal tunnel pressure (CTP), (ii) and contact stress induced by nerve impingement based on posture and force. Postures impacting CTP and contact stress are defined from: wrist flexion/extension angle, wrist radioulnar

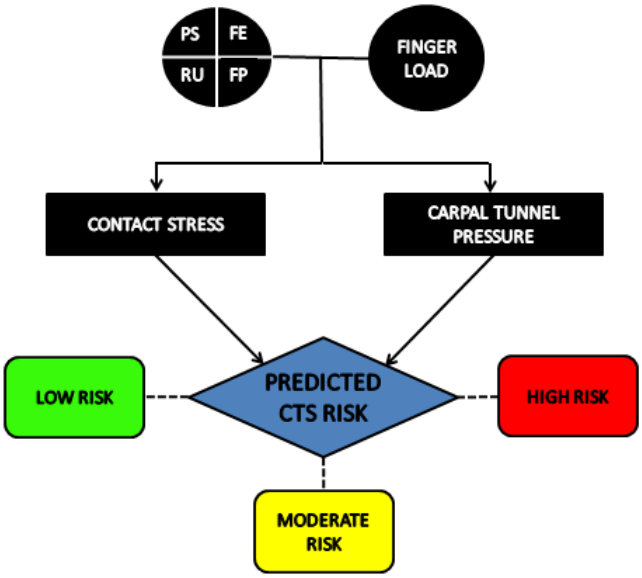


Figure 1.5: Global processing of the CTS model (PS: pronation/supination; FE: flexion/extension; RU: radial/ulnar deviation; FP: finger posture) (adapted from Weresch, 2011).

deviation angle, wrist pronosupination angle and finger posture. Force may be estimated from the external force applied at the fingertip and loading exerted to muscles crossing carpal tunnel. Thus, with the support of the McMaster Occupational Biomechanics Laboratory, the aim of this work was to develop a CTS risk model to understand and predict work-related disorders and injuries, taking automotive manufacturing as a basis of application and validation (see Figure 1.5).

A validation study has been conducted on a large sample of production line tasks for wrist and forearm postures. Workers' motion at an automotive manufacturing plant have been videotaped to evaluate hand, wrist and forearm postures of 20 production line workers. To provide confidentiality, only the arms and hands of the workers have been recorded on video. Six cycles of each task have been recorded from three angles to confirm postures and minimize parallax error. These data, along with the forces for the tasks (taken from job specifications) were model inputs, and the output of the CTS risk model has been compared to manufacturer injury data (first time occupational visits, lost time, etc.) to allow for the evaluation of the model. Only the comparative study will be presented here, as the CTS model has been fully described in (Vignais, Weresch, et al., 2016). 20 participants accepted to take part of the experimental protocol. All participants worked in the LEAR plant (Ajax, ON, Canada) at the moment of the study. Each participant worked in a different location inside the plant (fronts, outbound, rear, etc.) which means we analyzed 20 different workplaces with 20 different participants. Among participants, 6 women and 14 men participated in the study.

Two biaxial electrogoniometers (Biometrics Ltd, Newport, UK) were placed on each hand

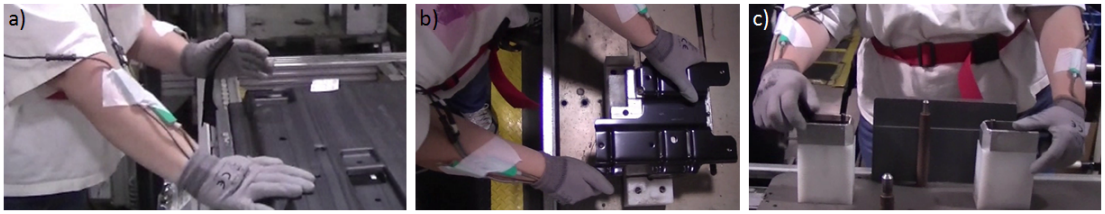


Figure 1.6: Video data from a job task in planes perpendicular: to wrist flexion/extension (a), to wrist radioulnar deviation (b), to wrist pronosupination (c).

and forearm by using double-sided tape. These electrogoniometers were used to measure flexion/extension angle and radioulnar deviation angle. A torsiometer measuring pronosupination angle was also positioned on the right side (see Figure 1.6). We were unable to put a torsiometer on the left side due to material limitation. Electrogoniometers and torsiometer were sampled at 50 Hz. Their respective cords were then connected to a data acquisition device (DataLOG, Biometrics Ltd) attached to the participant's waist using a belt. All cords were secured in place using medical tape. Participant was able to put their gloves back if necessary. Then participant put his wrist in neutral posture in order to zero electrogoniometers and torsiometer. Recording started from the data acquisition device after this procedure. The participant was then asked to return to her/his job inside the plant. Each work cycle was also filmed twice in three different planes: perpendicular to wrist flexion/extension axis, perpendicular to wrist radioulnar deviation axis, perpendicular to wrist pronosupination axis. These synchronized video capture planes have been used during the post-processing to estimate left pronosupination angle, finger posture and times when force was applied, as those biomechanical parameters were not provided by electrogoniometers and torsiometer.

Although current data have not been fully exploited for temporal and geographical reasons, a similar comparative study has been conducted to validate the CTS risk model (Weresch and Keir, 2018). The model predicted a mean time-weighted CTP of 21.3±0.4 mmHg (range 18.5- 27.8 mmHg). Evaluative results were promising, as CTS risk was slightly higher in jobs with a historical incidence of CTS. However, too few CTS claims existed to develop a strong correlation, thus creating a need for further refinement and investigation about the model.[1].

[1] I was a postodoctoral fellow in the McMaster Occupational Biomechanics Laboratory at McMaster University from 2012 to 2014 under the supervision of Pr Keir. This collaboration continued as Pr Keir came in France in 2019 for a plenary presentation when I organized an International Workshop untitled "Physical ergonomics and human motion analysis" at Université Paris-Saclay in 2019.

1.2.1.2 Influence of the support for order picking tasks

Analyzing occupational movements from electrogoniometers may be performed in other work environments. As an example, the success of drive-in supermarkets necessitated the development of new jobs dedicated to picking orders in storage area. These workers are continuously performing repetitive movements, awkward sustained postures, manual handling tasks followed by pushing and pulling tasks. As mentioned above, all these movements represent potential risk factors to develop work-related MSDs. It has been previously showed that drive-in employees expressed physical pains at lower-limbs, lumbar region, shoulder joint, elbow joint, wrist joint and hand levels (Brion et al., 2018). In 2018, I supervised a Master student on this topic. Camille Besombes, who was involved into the Master 1 program untitled 'STAPS : Ingénierie et Ergonomie de l'Activité Physique' from Université Paris-Saclay, performed her internship into a drive-in supermarket. The aim was to study the influence of the support for order picking activities (Besombes et al., 2019). In this study, it was decided to focus on upper-limb physical constraints related to elbow and wrist joints only. Moreover workers were able to use two different manual supports to prepare orders: a cart or wheeled-based containers. To prevent the development of WMSDs, joint comfort zones have been defined from the literature (Kee and Karwowski, 2001). Concerning the elbow joint, a comfort area between 60 and 100° of flexion can be deduced from the RULA methodology (McAtamney and Corlett, 1993). At wrist level, a flexion/extension of the wrist between 0 and 15° may be considered at ease (HSE, 1990). The same values can be defined for radial deviation. For ulnar deviation, the range of comfort motion would be between 0 and 5° (Hsiao and Keyserling, 1991). 17 workers have been recruited to participate in the study (7 women and 10 men). Four wireless electrogoniometers (Biometrics Ltd, UK) were used to measure right and left joint angles at elbow (flexion/extension) and wrist (flexion/extension and radioulnar deviation) levels during the task (see Figure 1.7). Electrogoniometers were sampled at 1000 Hz and they were initialized in anatomical neutral position. A video camcorder was also used to film workers during order picking (30 Hz) and thus relate significant value to worker's motion. After installing electrogoniometers, each participant was asked to pick order as naturally as possible.

Data were collected during orders performed with a cart (two repetitions), and orders performed with wheeled-based containers (two repetitions). Independent variable corresponded to the type of manual support used during order picking, *i.e.* cart or wheeled-based containers. Dependent variables were the percentage of time spent at a risky angle for flexion/extension of the elbow, flexion/extension of the wrist, and radioulnar deviation of the wrist for both sides. Results showed that wrist extension was maintained at risk during almost half of the task, with a risky wrist radial deviation also sustained. However, there was no statistical difference of the percentage of time spent at a risky level for the wrist between orders performed with a cart and with containers. This

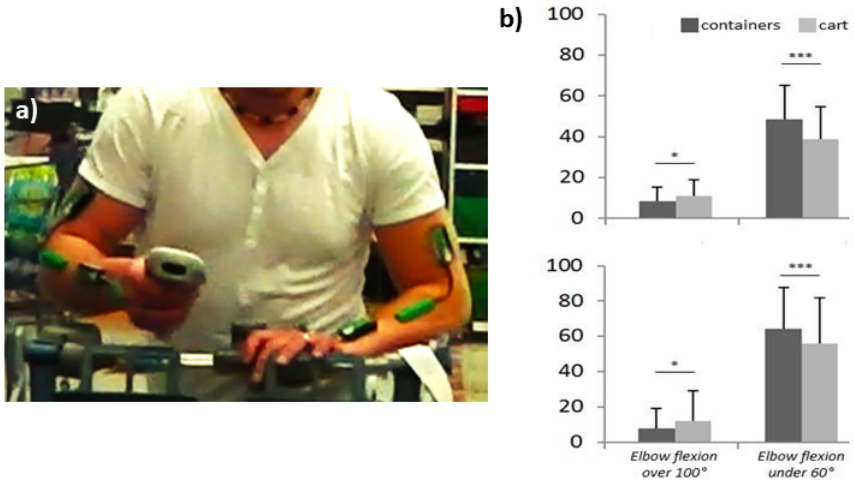


Figure 1.7: Goniometers placed at elbow and wrist levels during the order picking activity (a), and significant percentage of total time spent at a risky elbow joint angles according to the support, for right (up) and left (down) sides (b) (adapted from Besombes et al. 2019).

statement concerned risky angles of flexion, extension, radial and ulnar deviation. Despite the fact that the wheeled-based container induced supplemental manual handling tasks compared to the cart, the percentage of time spent at a risky level while picking orders was not significantly different in that condition. At elbow level, participants spent significantly more time at a joint angle over 100° when using the cart. This posture was likely used by workers to push the cart more efficiently with increasing load while picking order (Resnick and Chaffin, 1995). Conversely, participants exerted a joint angle under 60° significantly more often when using wheeled-based containers. Moreover, this risky angle was sustained by workers during almost half of order picking. Given the fact that an elbow joint angle between 0 and 60° also means having forearm in an extended posture, it might be more hazardous for the development of work-related MSDs, *e.g.* with a load in the hand (Rose et al., 2000). Results of this study highlighted the need to increase the height of the container, or to add a steering bar to the wheeled-based container, *e.g.* fixed between 90 and 115 cm as suggested by the ISO 11228-2 standard (ISO, 2007). Thus, this applied investigation allowed to prescribe ergonomic adjustments that need to be implemented to ensure prevention of MSDs for picking order workers. It has to be noted that this study has been accepted as a plenary presentation during the 2018 French Society of Biomechanics (Besombes et al., 2019)[2].

[2]After a 2nd year of Master STAPS : Ingénierie et Ergonomie de l'Activité Physique (IEAP) at Université Rennes 2, Camille Besombes is now Project Manager in an Occupational Safety and Health department (Bridor, 35).



Figure 1.8: Goniometers placed at wrist and elbows levels during the goods reception activity (extracted from Varraut, 2018).

1.2.1.3 Effect of the redesign of a reception area on the ergonomics of the upper body

This kind of methodology has also been applied to validate the redesign of a professionnal area in a large sport store (Varraut, 2018). The aim of this investigation was to conduct an ergonomic assessment with on-body sensors at two different moments: before and after the redesign of the reception area of this store. Firstly, an ergonomic assessment has been conducted on five workers while sorting goods after a reception using three dependent variables: RULA scores, a Nordic questionnaire and a task efficiency index. RULA scores were computed with joint angles obtained with goniometers placed on wrists, elbows, shoulders, neck and lumbar areas (see Figure 1.8). A Nordic musculoskeletal questionnaire is also filled by each participant before starting the experiment (Kuorinka et al., 1987; Roquelaure et al., 2006). It is a standardised questionnaire developed to identify MSDs affecting a worker's upper body which consists of binary and multiple choices questions about musculoskeletal state that can be answered directly by the worker. The questionnaire starts with general questions such as working conditions and physiological information (age, sex, height, weight). Then it is followed by a summary part where the worker indicates body zones at which he/she recently suffered from disorders. Finally the questionnaire is concluded by specific parts with more precise questions about suffering areas. These answers were used to link disorders and injuries to ergonomic scores. The task efficiency index was the ratio between the quantity of goods received and the time required to process goods sorting (on a basis of 10 receptions).

This protocol was repeated two times: one before and one after the redesign of the reception area.

Results did not show a significant decrease, both in global RULA scores and Nordic questionnaires. However, the task efficiency index was significantly improved after the redesign of the reception area. Thus, although outcomes of this applied study should be interpreted with caution given the low number of participants, decreasing the risk of MSDs seems to be accompanied with a better productivity, as previously showed in the literature (Chintada, 2022)[3].

Electrogoniometers may also be used to assess ergonomics for transportation and mobility. In a study performed at Université de Technologie de Belfort-Montbéliard, egress and ingress postures were analyzed on a physical mock-up of an innovative vehicle dedicated to mail delivery in order to suggest design recommandations (Roger et al., 2018). The influence of three seat heights, two headlining heights and three headlining widths were tested while six participants performed a simulated mail delivery task. Based on goniometers and video observations, a Rapid Entire Body Assessment (REBA) was conducted. Perceived discomfort was estimated with a Category Partitioning Scale (CP-50). Results showed that REBA scores were mainly at medium risk and discomfort scores were significantly influenced by seat height. REBA scores and discomfort scores were significantly higher for the lowest headlining height and the highest headlining width. Outcomes of this study permitted to establish that: the seat height has to be adjustable (between 580 mm and 760 mm), the headlining height has to be fixed to 1360 mm, and the headlining width has to be comprised between 300 and 525 mm for this vehicle.

1.2.2 Ergonomic assessment based on IMUs

Craftsmen are among the most exposed workers to MSDs, facing regularly repeated movements, force exertions and awkward postures (Das et al., 2018). To prevent these disorders during saddle manufacturing (Voltaire Design, Bidart, France), an ergonomic assessment has been conducted by using the RULA method (Caen et al., 2018). More precisely, the ergonomic assessment methodology was applied to lacing and joint workstations (n=4). Concerning the RULA method, joint angles were obtained from nine wireless IMUs (Trigno wireless system, Delsys, USA) directly placed on the participant (occiput, T5, sacrum, upper arms, forearms, back of hands) (see Figure 1.9). The IMU system was first calibrated during a reference position with hands in pronosupination, and then movements of the upper body, *i.e.* joint angles of wrists, elbows, shoulders, neck and lower back, have been collected during 20 minutes at 150 Hz. Joint angles were used *a posteriori* to compute global and local RULA scores, automatically and at each time frame. Thus RULA scores were not only a discrete value representing a whole activity, but also a continuous quantity reflecting segmental coordination and specific joint involvement during the task. Moreover, by

[3] After obtaining his Master STAPS : IEAP diploma at Université Paris-Saclay in 2018, Garbiel Varraut is now Robotic Storage Platform Area Manager (Amazon, 91).

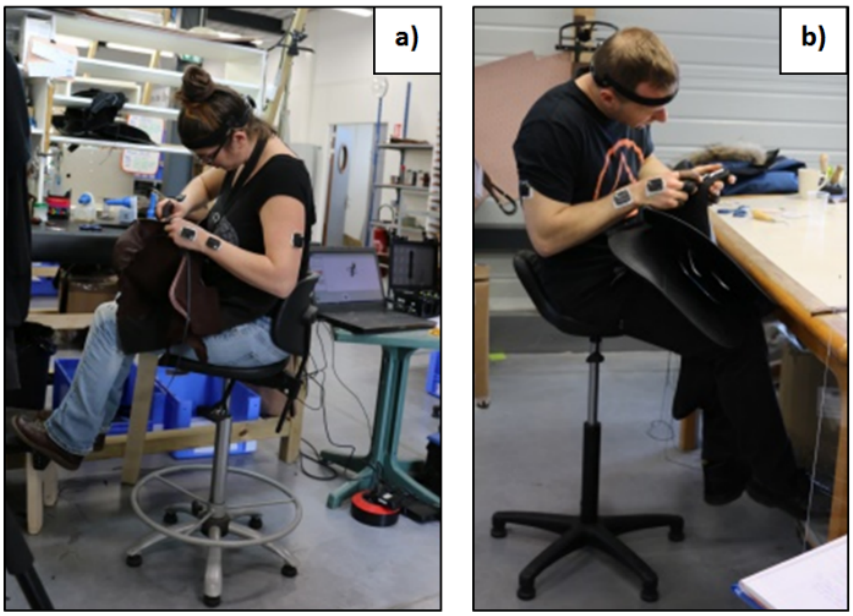


Figure 1.9: Motion capture with IMUs during joint (a) and lacing (b) activites (from Caen et al. 2018).

using joint angle thresholds previously defined in the literature (Vignais, Bernard, et al., 2017; Vignais, Miezal, et al., 2013), it was possible to deduce moments for which articulations were specifically at risk during manual tasks.

Results showed critical global RULA scores for both lacing (5.78±0.46) and joint (6±0.21) workstations, highlighting the need for a redesign of the workstations or an assistance during the activity. Time percentages showed that craftmen spent more time at a global score of 5-6 during the joint activity. Local scores showed that wrists and hands were above the risky threshold during the lacing activity. This study permitted to suggest ergonomic recommendations like an hanger arm for maintaining the saddle, or adjustable footrests for a better posture. It has to be noted that this study has been accepted as a plenary presentation during the 2018 ErgoIA conference (Caen et al., 2018)[4].

[4] After following the Master program at Université Paris-Saclay from 2016 to 2018, Nima Caën is now yoga teacher.

1.2.3 A combined approach to ergonomic assessment

1.2.3.1 On-body sensor network combined to videotaping for a subtask analysis

Many aspects of industrial work are of a physical nature, especially manual tasks, *e.g.* when the human worker has to pick up a component or arrange it in the assembly position. More generally, any kind of physical activity, such as lifting, pushing, pulling, carrying, moving, manipulating, holding or restraining objects, is considered to be a manual task (COSH, 2010). The current methodology being dedicated to upper body and upper limbs ergonomic assessment, it has been also applied to different industrial manual works. From 2014 to 2015, as an assistant professor at Université de Technologie de Belfort-Montbéliard (France) working in the Ergonomics and Conception of Systems department, I had the opportunity to closely work with industrial companies as Merck Millipore (Molsheim, France). This company is working on water purification activities, and is thus developing water processing systems on a large scale. This was the starting point of the collaboration: Merck Millipore aimed to prevent MSDs for operators working on assembly lines of their products, and it was a relevant framework for applying our methodology in order to orientate the ergonomic recommendations for the redesign of a risky workstation in an industrial field. The concerned workstation aims to clean filters dedicated to medical material (see Figure 1.10c). More precisely, the worker had to clean each subpart of the filter, to put subparts together, to vacuum the filter, and then to check the quality of the vacuuming. Then, each filter was placed inside a packet and sealed using a vacuum sealer. The ergonomic analysis was performed with IMUs placed on the operator's body (see Figure 1.10a, b) in order to automatically compute RULA scores.

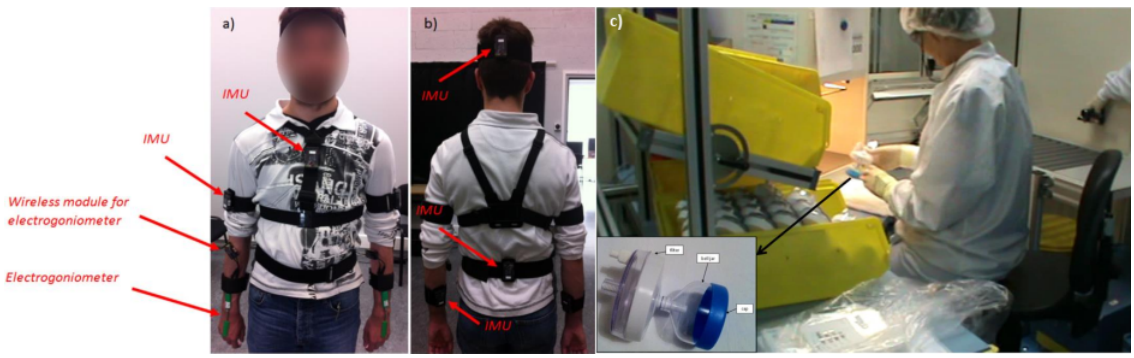


Figure 1.10: Placement of IMUs, electrogoniometers and their wireless modules in the front (a) and back views (b). Workstation dedicated to filter cleaning and description of the filter (c) (from Vignais, Bernard, et al., 2017).

The IMU system was composed of seven wireless IMUs (TEA, Nancy, France). Each lightweight sensor (32 g, 60 x 35 x 19 mm) contains a tri-axial accelerometer, a tri-axial gyroscope and a

tri-axial magnetic sensor. All sensors were sampled at 64 Hz. The IMUs were placed on the worker's body using manufacturer's guidelines and specific adjustable straps: one IMU for each upper arm, one IMU for each forearm, one IMU for the head, one IMU for the trunk, located on the chest, and one IMU for the pelvis, placed on the sacrum (see Figure 1.10a, b). This last IMU was necessary to define the movement of the trunk with respect to the pelvis segment. To record wrist angles (flexion/extension, radial/ulnar deviation), two bi-axial electrogoniometers (Biometrics Ltd., Newport, UK) have been added to the on-body sensor network and placed on both sides of the wrist using medical tape and straps. They were sampled at 32 Hz and synchronized with the IMUs during the post-processing through CAPTIV software (TEA, Nancy, France). At the workstation, all sensors were zeroed using a calibration posture (standing posture with upper limbs along the body, hands turned inside). This posture was also used at the end of the experiment to verify that the IMU signals have not been disturbed through the work cycles.

Wrist, elbow, shoulder, neck and back joint angles were deduced from the on-body sensor network through a biomechanical model developed by the manufacturer (TEA, 2014). This model was composed of 20 degrees of freedom. Joint angles were then used to compute automatically **global scores**, *i.e.* the resulting score ranging from 1 to 7 computed for each body side, and **local scores**, *i.e.* underlying scores associated to each segment into the RULA table (see Figure 1.2).

The originality of this study comes from the use of a synchronized camcorder in order to segment subtasks and relies subsequent ergonomic scores. Thus two camcorders have been used to film worker's activity. One camcorder was fixed on a tripod placed to the rear up of the worker (see viewpoint in Figure 1.10c). One camcorder was hold by the experimenter during the whole recording to capture postures of the worker's forearms and hands, especially on the right side of the workstation while the worker opened and closed the vacuum sealer. Both camcorders were synchronized to the IMU system and goniometers through a specific step into CAPTIV software. The worker was asked to perform 30 cycles of the task, which corresponds to 20 min of work. The analysis was conducted on the 10 cycles situated in the middle of the work done. Concerning the subtask identification, an ergonomic research technician used both video observations to manually code each worker's activity.

Results showed that participants performed the 10 work cycles with a global RULA score of 6±0.87 for the right side and 6.2±0.78 for the left side, meaning that the average posture used by the workers needed further investigation and it had to be changed soon (McAtamney and Corlett, 1993). Workers spent dramatically the biggest part of their time at a range of 7 (see Figure 1.11a). Average workers' local scores showed that 'Shoulder and upper arm', 'Neck and head' and 'Pelvis and trunk' scores were under the risky threshold, although 'Elbow and lower arm' scores were over the threshold as well as 'Wrist and hand' scores. Over time, elbows and lower arms were at a high level

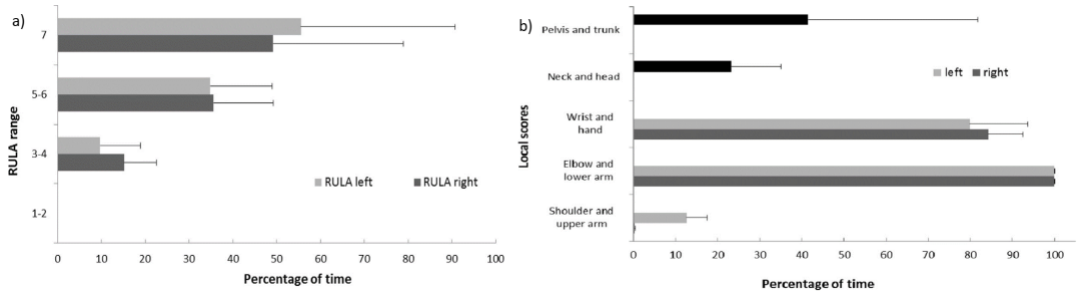


Figure 1.11: Percentage of time spent at each RULA range for global RULA scores (a), and percentage of time an articulation/segment spent at a risky level for local RULA scores (b) (adapted from Vignais, Bernard, et al., 2017).

of risk during a work cycle (100% for right and left sides). Wrist and hands were also exposed to a risky level for much of the period of work (see Figure 1.11b). Finally the subtask analysis based on videotaping revealed that the posture associated to the highest RULA score was 'snow thrower' for the right side, and 'opening the vacuum sealer' for the left side. Thus, shoulders and upper arms were most exposed during these two tasks for the right and left sides, respectively. Concerning elbow and lower arm, there were more at risk during 'opening the vacuum sealer' for the right and left sides. The 'cleaning' subtask was the most awkward for the right wrist and hand, the 'storing' subtask being the riskiest for the left wrist and hand. The neck and head were most exposed during the 'snow thrower' subtask, whereas pelvis and trunk were most at risk during the 'storing' subtask

Thus this ergonomic assessment based on on-body sensors synchronized with videotaping permitted a deeper analysis based on each subtask composing the work cycle. Thus each subtask was associated to: a mean RULA score, percentages of time spent at each RULA range, a local score per articulation/segment, and percentages of time each articulation/segment spent at a hazardous level. In terms of ergonomic recommendations, the future workstation would ideally have to reduce the movements of lower arms (by decreasing the workspace and the position of the useful elements for instance) and hands (by adapting the height of the workstation to each operator for example). Moreover, the highest RULA scores were obtained for the subtasks 'snow thrower', 'storing', 'closing' and 'opening the vacuum sealer'. Thus, the future workstation might integrate a support inside the snow thrower permitting to decrease the time where lower arms were in extension. In addition, the position of the vacuum sealer into the workstation might be redesigned as well as the way to open it (another activation pedal might be conceived to this aim).

Research works presented in this section included modeling, sensing, analyzing and assessing steps of the overall approach previously introduced (see Figure 1.4). Based on a certain biomechanical model (*e.g.* the human upper body in Vignais, Bernard, et al., 2017), different types of sensors are

selected (*e.g.* IMUs and electrogoniometers) in order to compute a risk of exposure (*e.g.* global and local RULA scores over time) during the occupational activity. This risk of exposure is compared between subtasks to assess relative differences in biomechanical exposure. Thus, this methodology allowed to develop innovative ergonomic metrics (*e.g.* local RULA scores) to identify risk factors *a posteriori*. This identification may serve as an input for ergonomic recommendations in order to redesign the workplace, and evaluate the impact of a modification in processes associated to the occupational activity. Some companies began to use this kind of process for their ergonomic consulting activities (*e.g.* Moovency in Rennes or Moten in Nanterre).

1.3 Extending the methodology to real-time feedback

Previous studies did not take full advantage of wireless wearable sensors solution. Indeed, this ergonomic interaction loop would permit to compute biomechanical exposure assessment in real-time for a direct modification of the motor activity through feedback. This kind of research will be presented in the next section. Firstly we will extend previous risk exposure assessment with a real-time ergonomic feedback provided through an Augmented Reality (AR) solution (Vignais, Miezal, et al., 2013). Then we will demonstrate the interest of integrating on-body based biofeedback into a serious game to design future motor therapies (MacIntosh, 2020).

1.3.1 On-body sensor network combined to augmented reality for online ergonomic feedback

Generally, ergonomic assessment of industrial manual tasks are performed offline. However, real-time postural evaluation may provide benefits in practice (Battini et al., 2014; Mullineaux et al., 2012). If the system provides the worker with information concerning his current ergonomic behavior, then postures could be modified immediately. Furthermore, in the long run, associations between certain postures and their hazardousness could be learned. To facilitate the immediate feedback rendering, AR technology can be used during the actual work execution (Udani et al., 2012). As previously highlighted, IMUs may offer potential for regular motion capture in an industrial context, as it is a suitable device for monitoring the kinematics of a segment in real-time (Breen et al., 2009). In the framework of the COGNITO European project (EU FP7 2007-2013 grant agreement n° 248290) which aimed to help workers performing industrial manual tasks, a on-body sensor network was designed by using wired IMUs (Trivisio GmbH, Trier, Germany) and electrogoniometers (Biometrics Ltd, Newport, UK) (see Figure 1.12) (Vignais, Miezal, et al., 2013). A biomechanical model of the upper body was derived from sensors (all sampled at 100 Hz), composed of 10 rigid segments (trunk, clavicles, upper arms, forearms, hands and head) connected by anatomically restricted articulations (pelvis, neck joint, sternoclavicular joints, shoulders, elbows and wrists) resulting in 20 degrees of freedom. One of the originality of this model comes from the fact that the sternoclavicular articulation was integrated into the model, depending on the upper arm abduction angle (Klopcar and Lenarcic, 2005). Segmental lengths were derived from an anthropometric database by using the worker's height as input (Winter, 2009). A calibration process permitted to define the orientations of the IMUs with respect to the body.

A see-through head mounted display (HMD) was used to allow an online ergonomic visual feedback (see Figure 1.12). To this aim, joint angles were computed in real-time from the biomechanical model, by using a set of loosely coupled extended Kalman filters (model-based sensor fusion)

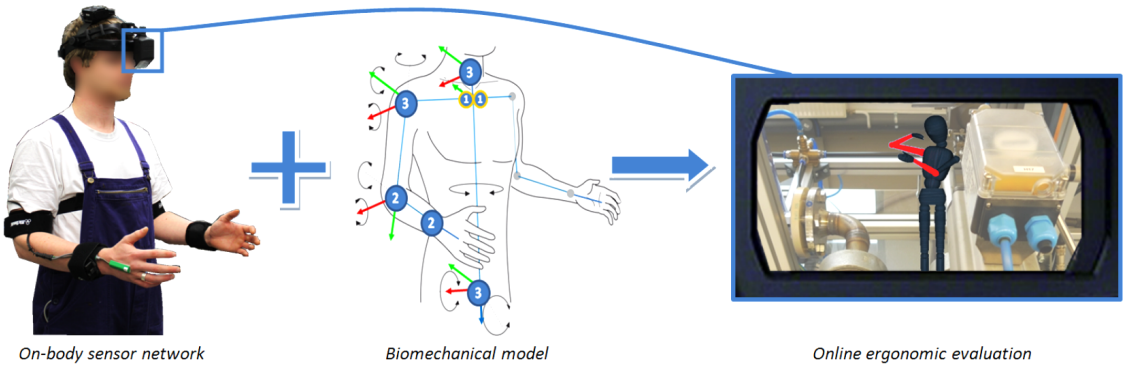


Figure 1.12: On-body sensor network composed of IMUs coupled with goniometers (left) and underlying biomechanical model of the upper body (middle) with rotation axes for local body frames, and degrees of freedom of each joint, allowing a real-time ergonomic feedback into the HMD (right) (from Vignais, Miezal, et al., 2013).

(Bleser et al., 2011). Wrist angles were given directly by goniometers. The ergonomic scores and corresponding feedback were derived from tle RULA method. Two feedback modalities were selected: an auditory signal linked to the global score and a visual cue related to local scores provided through the see-through HMD. To validate this system, a pilot study has been conducted on two groups of workers performing standardised industrial manual tasks, with (n=6) and without (n=6) the real-time ergonomic feedback. The experimental task scenario was chosen to contain different postures and motions that are performed in industrial manufacturing: turning levers, removing fuses at knee level, using a screwdriver, etc. For the two groups, the execution times and the percentage of time spent at each range defined by the RULA table were computed. Moreover, an articulation-based analysis was carried out based on predefined thresholds associated to local scores, allowing the computation of the percentage of time spent at a risky level per articulation or segment during the task.

Despite the fact that the group with feedback needed significantly more time to execute the whole task compared to the group without feedback, the execution time, *i.e.* effective time to complete each subtask, was similar between the two groups. One of the main result from this study is related to the fact that on average, participants with the feedback performed the task with a significantly lower global RULA score (3.95±0.83) than the WOR group (4.35±0.54), thus having a lower risk to develop MSDs. Percentage of time spent at each RULA range demonstrated that there were some significant differences between the two groups for ranges 3-4 and 5-6 (see Figure 1.13a). The percentage of time spent at a risky level per articulation or segment during the task showed that subjects' articulations and segments without feedback were significantly more exposed to a risk of MSDs during the task, especially for the left upper arm, the left lower arm, the right upper arm,

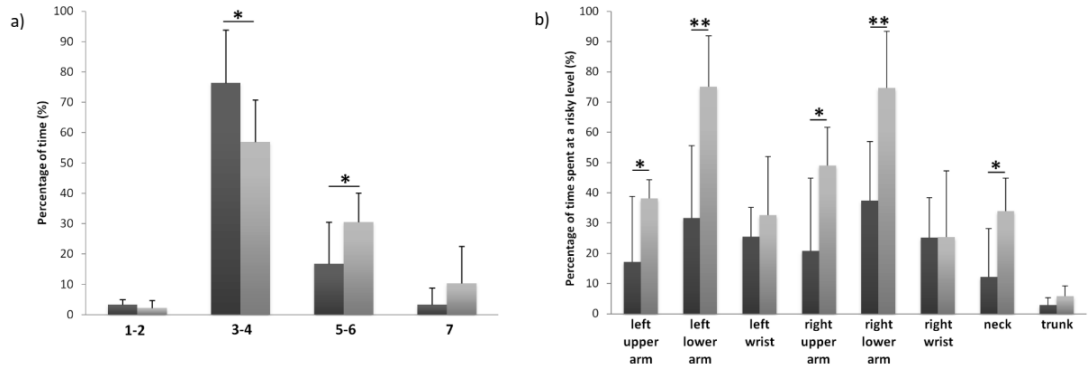


Figure 1.13: Percentage of time spent at each range during the task (a), and percentage of time spent at a risky level per articulation or segment (b) for groups with (black) and without (grey) RULA feedback (* $p<0.05$, ** $p<0.01$) (from Vignais, Miezal, et al., 2013).

the right lower arm and the neck (see Figure 1.13b). Subjective reports confirmed the design and efficiency of such a feedback for ergonomic perspectives.

The proposed innovative approach can be considered as a complementary tool for ergonomic evaluation in industry. After designing an occupational workplace, the current real-time ergonomic feedback could be employed to validate the design, refine the industrial environment and improve required movements to decrease the risk of MSDs. Although visual-auditory feedback has been proven to improve user performance in AR studies (Breen et al., 2009; Burke et al., 2006), further developments concerning multimodal feedback extracted from a human motion might be necessary as information fed back to the worker must be both salient and not distracting in an industrial environment. Few other studies used a real-time feedback to produce an ergonomic intervention in different applications. A vibration-based posture correction sensor was used to correct head and neck posture in sitting and standing position at the office (Ailneni et al., 2019). Along the same lines, Bootsman and colleagues developed an instrumented shirt with a combined visual-auditory-vibrotactile feedback given on a smartphone (Bootsman et al., 2019). Real-time IMU-based ergonomic systems have been developed to provide a visual feedback on a remote screen: for manual material handling in warehouse environments (Battini et al., 2014), with additional EMG for super-market cashiers (Peppoloni et al., 2016), and for construction workers with auditory-vibrotactile feedback possibilities (Valero et al., 2016). Thus, it appears that combining feedback functions into the sensor unit itself (*e.g.* vibrotactile into goniometer, visual into IMU for the head) might be an interesting way to provide online feedback about potentially harmful work postures or activities. Moreover, visual displays might be more effective when the viewer is not the worker, but rather a work-supervisor, manager, or ergonomist who is reviewing a workers' cumulative biomechanical exposures across time.

The story behind
I was a postdoctoral fellow at Université de Technologie de Compiègne between 2010 and 2012, working on the COGNITO European project. Although it was not planned initially, I suggested to add an ergonomic analysis of the upper body in discussion with my supervisor Pr F. Marin, given the fact that we had access to all necessary information to compute RULA scores. My German colleagues, Gabriele Bleser and Markus Miezal, were clearly an outstanding support for this achievement as they integrated the whole code permitting to compute RULA scores (from Matlab to C++) into the IMU-based biomechanical model. Katharina Mura dealt with subjective questionnaires and Dominic Gorecky gave full access to the Smart Factory plant in Kaiserslautern. I remember that first discussions and conceptions we had about this study with Gabriele and Markus were in a cab, in Portugal in 2010, after a project meeting... This article has now been cited more than 300 times.

1.3.2 A biofeedback-enhanced serious game to improve motor function in youth with cerebral palsy

Investigating the impact of a real-time ergonomic assessment may be interesting for future methodologies as this sensory feedback is critical when implementing strategies to improve motor activities (Van Dijk et al., 2005). Feedback impacts how well tasks are learned, a person's focus and their motivation (Wulf et al., 2010). Feedback can be 'task-intrinsic' or inherent, corresponding to the natural perception within the individual. Alternatively, feedback can come from an external source. In our case, external feedback was information from a device or a person, and it can be given to the individual during or at the end of the task (Van Dijk et al., 2005). In the text that follows, the term *biofeedback* will be used to refer to external feedback, when a person receives information about his/her body state (*e.g.* hand position, muscle activity, ergonomic risk), to increase awareness and inform the individual to how their body is functioning (MacIntosh, 2020). A game-based approach may also enhance learning and training methodologies. Rather than passive observers, users engage in those learning environments as active participants, permitting the development of exploration-based learning paradigms (Checa and Bustillo, 2020; Wulf et al., 2010). This may be of prime importance in the rehabilitation area when dealing with the design of innovative motor therapy. Indeed, rehabilitation research including physical and cognitive work that incorporates VR-based interventions, has been recently on the rise due to the ability to create programmable immersive experiences that can directly influence human behavior (Elor, Powell, et al., 2022). Virtual environments with conventional therapies may be paired with high-fidelity technological instruments like motion capture. Through serious games, immersive environments are designed

to translate therapeutic goals into game mechanics, making the therapies more enjoyable and stimulating (Cherniack, 2011; Elor, Kurniawan, et al., 2018; Finkelstein and Suma, 2011; Gobron et al., 2015). Serious game, or interactive computer play, will be defined in this section as "any kind of computer game or virtual reality technology where the individual can interact and play with virtual objects on a computer generated environment" (Sandlund et al., 2011). The nature of the serious game allows researchers and service providers to build flexible environments that can adapt with the individual and provide therapeutically relevant feedback.

This approach may be applied to youth with cerebral palsy (CP). Indeed, CP is a common disability related to an injury or abnormality of the brain occurring near birth which persists from childhood through adulthood (Rosenbaum et al., 2007). This may impact a person's motor control, perception, intellectual function, ability to perform daily activities (*e.g.* walking, eating), and participation in society (Novak et al., 2013). The condition is generally classified based on the affected body region(s) (*e.g.* hemiplegia, diplegia) and the type of tone or movement abnormality (*e.g.* spasticity, dyskinesia). However, there is great overlap and variability across the spectrum of individuals with CP. The sensory deficits some people with CP experience may also contribute to reduced performance. Sensory information is used continuously for movement planning and error correction, which in turn, is used to learn and improve motor skills (Scheidt et al., 2005). When an individual with CP has proprioceptive, tactile and motor deficits, this feedback loop is inhibited, impacting motor control. Conventional motor interventions for youth with CP usually require frequent and intense practice. For A. MacIntosh's cotutelle doctoral project (2016-2019), the serious game consisted in a video game where a player did therapeutic movements to control game actions on-screen (MacIntosh, 2020). It was an attractive way to augment traditional therapy and align with children's interest as it has been showed that eight of ten young people with CP enjoy playing video games recreationally (Shikako-Thomas et al., 2015). Moreover, serious game has been used to improve balance (Jelsma et al., 2013), gait symmetry (Levin et al., 2017), upper limb strength (Keller and van Hedel, 2017) and occupational performance in children with unilateral CP (James et al., 2016).

The originality of this serious game approach for rehabilitation is related to the integration of *biofeedback* into the serious game. Biofeedback can be used to represent any biological variable, *e.g.* arm orientation while reaching (Huang et al., 2006), muscle activity patterns during walking (Colborne et al., 1994), or changes in center of mass while running (Eriksson et al., 2011). This information can be delivered in a variety of ways such as a visual graph of muscle activity, an audio tone to indicate pace during walking, or a vibration when moving away from a target (Sigrist et al., 2013). Biofeedback can help increase awareness and control that would normally be unnoticed. This can be particularly helpful for some persons with CP who may have sensory impairments and are less able to use intrinsic feedback (Rosenbaum et al., 2007). Additionally, persons with CP

have shown difficulty with movement initiation and prediction (Green and Wilson, 2012), and a greater reliance on visual strategies (Williams, Anderson, et al., 2011). Given the extent of motor and sensory deficits in people with CP, biofeedback is well suited to enhance quality of training. In this project, biofeedback was used to address movement initiation/termination, muscle weakness and selective motor control. Thus the goal of this doctoral project was to leverage the motivational and immersive aspects of serious game and combine them with evidence-based biofeedback to improve at-home manual therapy activities for youth with CP. To this aim, a three-step framework was defined:

- First, the quality of evidence of biofeedback interventions used towards improving motor activities in people with CP had to be evaluated. This step allowed to identify key elements of biofeedback that need to be implemented in interventions for people with CP (MacIntosh, Lam, et al., 2019; MacIntosh, Vignais, and Biddiss, 2017).
- Secondly, a collaborative approach including young people with CP, clinicians, and game developers permitted to integrate biofeedback into a commercial video game, and familiarize youth with CP to control a commercial video game using therapeutic hand gestures (hand opening/closing) (Macintosh et al., 2021; MacIntosh, Vignais, Vigneron, et al., 2022).
- Thirdly, the feasibility of the biofeedback-enhanced serious game activity was assessed within a home-based intervention protocol (MacIntosh, Desailly, et al., 2020).

It has to be noted that this cotutelle doctoral project was conducted in collaboration with University of Toronto (Canada), Université Paris-Saclay (France), Université Evry-Val d'Essonne (France), Holland Bloorview Hospital (Toronto, ON, Canada) and Fondation Poidatz (Saint-Fargeau Ponthierry, France).

1.3.2.1 Evaluation of the quality of evidence of biofeedback interventions for people with CP

To understand how to optimize the quality of home-based therapy activities, a current state of the evidence was required. Several studies have investigated motor therapies that employ biofeedback. However, the diversity of task objectives and outcome measures that have been studied make conclusions regarding the effects of biofeedback difficult to synthesize. This systematic review identifies common themes between various outcome measures to understand the typical place of biofeedback in motor interventions and how it may be modified to better align with evidence in motor learning theory. The review includes quantitative study designs comparing pre post-intervention, no-feedback controls, or alternative feedback groups. To help classification of biofeedback design, key characteristics were deduced from previous literature in motor control

and motor learning in other populations (*e.g.* stroke), as well as individuals with CP (Colborne et al., 1994; Eriksson et al., 2011; Huang et al., 2006; Sigrist et al., 2013; Timmermans et al., 2009). These characteristics include: method of presentation, movement variable, focus of attention, timing, frequency, and autonomy (see Table 1 in MacIntosh, Lam, et al., 2019). Eight databases were searched for rehabilitation interventions that provided external feedback and addressed motor activities. Two reviewers independently assessed and extracted data (see Figure 1.14). The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) framework was used to evaluate quality of evidence for outcome measures (Schunemann et al., 2013) related to two International Classification of Functioning, Disability and Health chapters (Cieza et al., 2005). Through this evaluation, the relationship between feedback characteristics previously mentioned and effectiveness of the biofeedback interventions were explored.

From the 57 studies that met inclusion criteria, main results highlighted that the Quality of Evidence level is "Positive Very Low" for outcomes related to serious game Activities and Participation, and Body Functions. This GRADE level is attributed to the number of non-controlled studies and the heterogeneity of outcome measures. Despite this, biofeedback interventions generally showed improvements in measures of motor activity pre–post-intervention. Frequently, studies implemented characteristics of biofeedback incongruent with motor learning principles expected to facilitate sustained results. By using a strategy that facilitates self-regulation, self-efficacy, and a common set of outcomes, it appears that biofeedback has the potential to improve motor rehabilitation for people with CP. More precisely, this review identified three characteristics of biofeedback were consistently underused or forgotten in motor rehabilitation interventions for people with CP although they have been identified in motor learning literature as having important roles towards faster and sustained performance improvements (Sigrist et al., 2013; Timmermans et al., 2009; Wulf, 2013). The three characteristics are:

- Autonomy: give users an active role in the decision to view and use feedback.
- Timing: combine terminal and concurrent feedback to strengthen the lasting impression of the activity.
- Focus of attention: connect the desired movement to game actions so that feedback is focused on game results.

These principles are used in the next section as a starting point for the co-creation process of the biofeedback-enhanced serious game technology. The principles established in this review were used in part to create a Biofeedback Infographic (see Figure 3.8 in Appendix), explained in the next section.

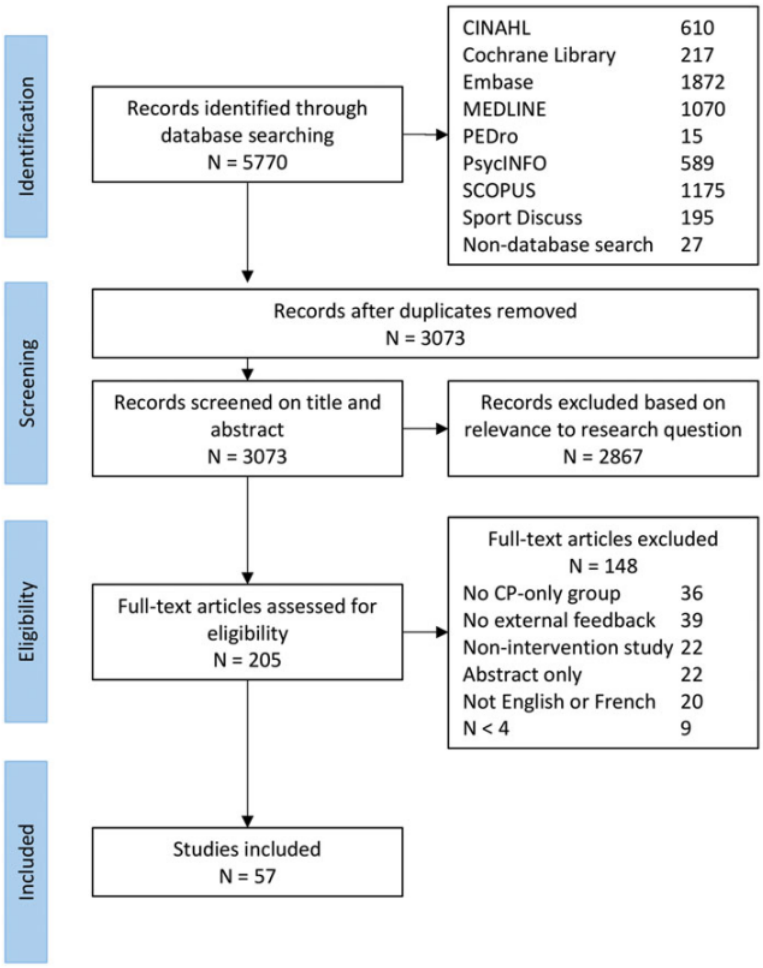


Figure 1.14: Preferred Reporting Items for Systematic Reviews and Meta-Analyses processing flow diagram (from MacIntosh, Lam, et al. (2019)).

1.3.2.2 Development of the serious game and biofeedback integration

The aim of this section was to design a biofeedback-enhanced serious game in collaboration with youth with CP, clinicians and game developers. This serious game has to integrate therapeutic hand gestures (hand opening/closing) into the video game. To this aim, interviews with co-creators have been conducted between April 2017-May 2018 in Canada and France. Firstly the co-creation design process and how theoretical biofeedback principals were practically implemented will be described (MacIntosh, Vignais, Vigneron, et al., 2022). Then the technical procedure developed during the co-creation process that allows users to play the game will be detailed (Macintosh et al., 2021).

Design and evaluation of biofeedback Nine young participants with CP (10-23 years old, with mild-moderately impaired use of one hand, Manual Abilities Classification System (MACS) level I-III (Eliasson et al., 2006)) were recruited to participate as 'design partners' to integrate evidence-based biofeedback principles into a commercial video game. As design partners, participants were consulted throughout the process from ideation to final product (Druin, 2010). Participants tested game prototypes during 1-hour sessions with a researcher. Three occupational therapists were also consulted and attended design sessions when required by participants. Biofeedback elements were added to the game and refined at each session. Researchers prompted participants to verbalize their thoughts related to biofeedback timing, aesthetic design, comprehension, and motivation during and after play-testing. Sessions were completed in an urban North American centre and a rural Western European centre to build biofeedback presentation receptive across cultures. After each design session, participant responses were synthesized, and changes were made to the game for the next session. These changes were recorded in an audit trail to keep track of the decisions made and rationale. After the end of the design phase, the therapy video game with integrated biofeedback was ready for testing in-home.

Biofeedback was added to the commercial game, 'Dashy Square' (KasSanity Inc., Canada). The game objective is to navigate through 10 levels of increasing difficulty without touching obstacles. Example gameplay can be seen here. In the game's original form, players press a key to evade obstacles. Working with the developer, controls were changed from a single key press to a gesture-based controller using EMG and inertial sensors detected with the Myo Armband (Thalmic Labs, Canada) (see Figure 1.15). Participants wore the Myo Armband on the forearm of their affected side. Raw data from the armband's eight-channel EMG and 9-axis IMU) were processed through custom scripts developed in MATLAB 2017b to interpret gestures and command the game. Participants and therapists were consulted to determine the desired gesture with which to control the game. Gestures were one of: wrist extension- active fingers, wrist extension- relaxed fingers, finger-thumb

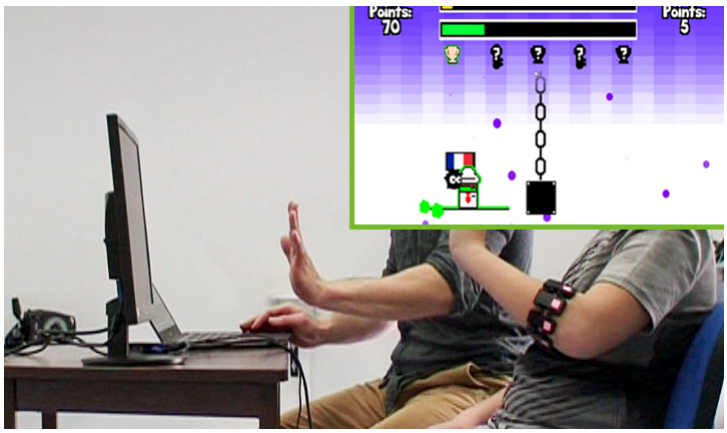


Figure 1.15: Example gameplay of the serious game adapted from 'Dashy Square'. EMG sensors from the Myo armband placed on the participant's forearm permitted to detect a wrist extension. This gesture will control the avatar upward to evade the obstacle.

pinch, supination.

The biofeedback was designed to reward completion of the therapeutic goals identified by clinicians and participants: making the gesture at the correct time and having high quality movement (*i.e.* low co-contraction and fewer compensatory movements). Specifically, co-contraction was quantified as the ratio between extensor and flexor muscle activity. High forearm extensor activity while keeping flexor activity low was associated with less co-contraction and higher quality movement. Compensatory arm movements were detected by the IMU and fewer arm movements, quantified by the resultant angular velocity variability of the forearm, were associated with more isolated hand movements and higher quality movement. During design sessions, participants tested the custom gesture-controlled version of Dashy Square with added biofeedback elements. Here is a synthetic list of biofeedback elements added to the video game following the co-design process:

1. *Dodge points* given for avoiding obstacles, linked to correct timing of a gesture.
2. *Style points* were linked to quality of movement, specifically the extent of cocontraction. Higher 'Style Points' means greater extensor and lesser flexor activity (less co-contraction).
3. *Speed-change* biofeedback events were linked to quality of movement, specifically the extent of compensatory arm movements. When compensatory arm movements were detected beyond an individualized threshold, game speed was reduced to give participants more time to perform gestures.
4. *Practice panels* were shown after consecutive poorly timed or executed movements. The practice panel offered a simplified game environment without obstacles wherein participants could practice the movement.

5. *End-of-level rewards*: Trophies were rewarded at the end of each level in accordance with the number of dodge and style points achieved. One trophy indicated a lower level of mastery while three trophies was associated with the highest level of mastery. Additional rewards such as unlocking characters and leader board standings could also be reviewed as end-of-level 'knowledge of results' biofeedback.

Usability and impact of the biofeedback were evaluated in a 4-week home-based intervention with 19 participants. There were ten females and nine males, 8-17 years old (11.7±2.5 years). Seven participants were considered MACS level II and 12 were at level I. Seven had mixed tone, one had mild dystonia and 11 had spastic hemiplegia. Approval was obtained by Holland Bloorview's Research Ethics Board (#18-785) and the French Comité de Protection des Personnes (CPP, #2018-A00536-49). The same protocol was approved for the feasibility study (see next section), only results concerning the impact of biofeedback elements will be presented in the current section.

Each participant took home a laptop with the game software and a Myo Armband to play for four weeks. Before playing alone, the researcher gave one or two training sessions to ensure participants could operate the system and understood the objectives and controls of the game. Participants created a self-defined practice schedule with the assistance of their caregiver and an occupational therapist (the suggested goal was 3-5 times per week, 30 minutes per session) (Golomb et al., 2010). At home, participants selected which level to play, but more difficult levels were unlocked only after finishing easier ones. Once per week, the researcher visited the participants to evaluate their motivation, adherence, collect system logs, and to record subjective biofeedback-related observations. The system automatically logged biofeedback usage data (*e.g.* dodge points, style points, practice panels presented) and physiological data (*i.e.* EMG, arm kinematics) for post-hoc analysis. At the end of the four-week trial, participants completed a semi-structured interview and a custom game-feedback questionnaire with the researcher. These were used to understand how the added biofeedback impacted the participants' experience with the game. The questionnaire was based on validated questionnaires for measuring usability (System Usability Scale (SUS) (Brooke, 1996) and enjoyment (Flow Short from Engeser (2012)) and questions developed during a previous study of interactive computer play games for young people with CP (Hernandez et al., 2018).

To assess if the biofeedback implementation was (i) efficient, (ii) effective, and (iii) engaging from the perspective of its users for promoting quality movement during a therapy game focused on hand gestures, the following variables were analyzed:

- *Efficiency*: The system was considered efficient if participants reduced the use of compensatory arm movements immediately after a speed-change biofeedback event. The difference in resultant angular velocity variability of the forearm between the five seconds before and five seconds after the speed-change biofeedback event was calculated. We refer to

this variable as the "change in arm movement."

- *Effectiveness*: The system was considered effective if task performance improved over time. Three indicators of task performance are the "dodge point rate" (dodge points accumulated per minute of play, linked to correct timing of a gesture) and "style point rate" (style points accumulated per minute of play, linked to co-contraction quality). The number of "practice panels shown per minute" was calculated as an indicator of the need for biofeedback. Practice panels were presented when consecutive poorly timed or executed movements were performed. As such, indicators of improved performance were: increasing dodge point rate, increasing style point rate, and decreasing number of practice panels shown per minute.
- *Engagement*: The system was considered engaging if participants chose to review the 'knowledge results' biofeedback provided at the end of each level reporting on their success in the game (*e.g.* the trophies awarded). This variable, 'review choice' is the proportion of opportunities participants took to see end-of-level 'knowledge results' biofeedback.

During the four-week intervention, participants played an average of 17±9 minutes/day, 4±1 days/week. Total practice time ranged from 37-333 minutes across the 19 participants. Participants averaged 2815±2202 repetitions over the course of the intervention. Only significant results will be described here. Concerning *efficiency*, all participants adapted their movements immediately after the biofeedback. On average, participants reduced arm movement by 10.2±4.0% in response to biofeedback. Participants continued to respond to the speed-change biofeedback across the intervention as practice time was not a significant predictor. Concerning *effectiveness*, practice time was associated with: scoring points faster, doing gestures with higher quality co-contraction, and seeing fewer practice panels. Participants felt also *engaged* in their practice as they chose to view their end-of-level 'knowledge results' biofeedback 65.4±22.4% of the time. This choice varied across participants but it was not dependent on practice time. To this point, 16/19 participants remarked that they decided to review their achievements as they aimed to get all the rewards in each level. Based on questionnaire results, it can be said that participants found the game highly usable, and partially-to-highly enjoyable. Semi-structured interviews revealed that, of the 19 participants, nine were motivated primarily by long term rewards (*e.g.* collecting trophies), seven focused on the immediate score, and three on their game rank relative to others. Learning from this co-design and evaluation process, some recommendations for an effective design of biofeedback in therapy gaming technologies have been proposed (see Figure 3.8). Development of the classification algorithms for detecting hand gestures and integrating biofeedback elements will now be described.

Gesture classification and calibration procedure In typically developing populations, many gestures (>10) can be classified with high accuracy (>95%) using aggregated data and large

training sets (Liu et al., 2016). However, in a clinical population like youth with CP, a personalized approach is necessary to address the individual's abilities, therapy goals and movement strategies. Myoelectric patterns are preferred here over optical inputs as it can support practice even when someone is capable of only small and inconsistent gestures. People with CP may have noisy neurological commands when gesturing (Kurz et al., 2014). The muscle command to generate a targeted movement (*e.g.* hand opening) can be accompanied by: inconsistent neural drive (spasticity or weakness), atypical forearm flexor and extensor muscles synergies (undesirable co-contraction), and movement artifact (impaired selective control) (Sanger et al., 2006). For these reasons, developing high-performing classifiers for people with CP can require substantial training, specialized hardware and interaction with clinicians or researchers. Using features specifically targeted to discriminating these signs of CP will facilitate home-based gesture classification and calibration. This subsection describes the in-home calibration and classification procedure embedded into the rehabilitation video game. The procedure allows for:

1. Home setup: training data are collected and processed with minimal adult involvement within the first minutes of gameplay.
2. Therapeutic practice: Real-time gesture recognition identifies therapeutic movements for game feedback and control.
3. Clinical insight: Features used for classification are associated with neuromotor signs of CP. These feature groups were 'uncommon relative muscle activities', and 'high movement variability', in comparison to traditional 'channel-independent' features.

To accommodate smaller arms, the original 8-channel device was cut to 4 or 6 channels and the software adjusts accordingly. This reduction does not introduce any bias since the collected signals are statistically independent of each other, whether there are 4, 6 or 8 channels. Participant's data were collected and used in the home-based rehabilitation video game through a specific procedure (see Figure 1.16).

The same population of 19 youth with CP composed the database for evaluating the classification and calibration procedure. During the game, the participants sat at a table in front of the laptop with the elbow at 90 degrees and the palm facing down. Participants and therapists decided together which gesture (on the four described previsouly, see 1.3.2.2) to practice and set the practice schedule. Most (17/19) participants practiced wrist extension (open or closed) for the entire activity. In all cases, participants aimed to keep the wrist in an extended or neutral position while performing the gesture (MacIntosh, Desailly, et al., 2020). Gestures were verified by visually labelling videos collected weekly by the PhD student during a game play session. A visual signal emitted from the game software synchronized video, EMG and inertial data. Initiation and termination of each gesture were labeled manually (True Labels) as a ground truth. Home-setup, therapeutic practice

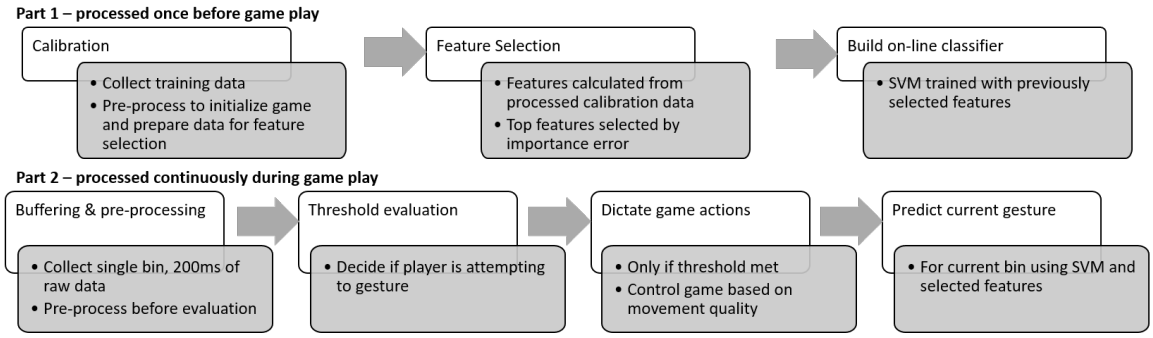


Figure 1.16: Overview of calibration and classification procedure to use EMG and inertial data as controller and feedback in rehabilitation video game. Phases are divided into steps required before and during game play. It has to be noted that when predicting the current gesture online, the support vector machine (SVM) may be used as feedback (*e.g.* higher points scored for the correct gesture) or as a control mechanism for the game (*e.g.* to execute a binary operation such as to jump over an obstacle). Full details of each step are described in (Macintosh et al., 2021).

and clinical insights have been evaluated through specific variables.

As a summary of the results, we can say that home-based calibration showed good agreement with video verified ground truths (0.86 ± 0.11, 95%; CI = 0.93-0.97). Across participants, classifier performance for the extension-open fingers gesture was 0.90 ± 0.05 (95%CI = 0.87-0.92) and, for extension-closed fingers gesture, 0.82 ± 0.09 (95%CI = 0.77-0.86). Features sensitive to signs of CP, *i.e.* 'uncommon relative muscle activities' and 'high movement variability' were significant contributors to classification and correlated to wrist extension improvement and increased practice time. A strength of the approach presented here is that feature selection was highly adaptable. Selected features were person-specific and updated weekly as the participant progressed. This allows for features of different channels to be included if they play a more prominent role in the target gesture and irrelevant features to be removed as gestures become more consistent.

1.3.2.3 Assessment of the feasibility of the biofeedback-enhanced serious game interventions

Once the biofeedback and gesture classification have been set up, it may be suggested that the success of the serious game intervention will be influenced both by the technology used, and previously tackled, and the supports provided. Thus a feasibility assessment of the biofeedback-enhanced video game has been conducted in combination with Solution Focused Coaching strategies (Abraham et al., 2009; Baldwin et al., 2013) in order to provide a motivational, goal-based environment to address muscle weakness and selective motor control. The objective of this



Figure 1.17: Summary of pilot feasibility study process and elements. Items in green are the study phases and duration. Items in blue indicate the tasks during each phase. COPM: Canadian Occupational Performance Measure; AROM: Active Range of Motion; AHA: Assisting Hand Assessment (see MacIntosh, Desailly, et al. 2020for more details).

feasibility study was to support development towards future randomized controlled trials and not to define statistical or clinical effectiveness of the intervention (Thabane et al., 2010). More precisely, we firstly assessed *process feasibility* of the biofeedback-enhanced therapy video game intervention protocol for young people with CP. The subobjective here was to determine the ability to enroll participants, enable home-based practice, and retain their activity during a 4-week intervention. To this purpose, a priori success criteria were established for the recruitment and response rates, adherence, and frequency of technical difficulties impeding home practice. Secondly, the *scientific feasibility* of the intervention was evaluated by estimating the effect size and variance for six person-centred outcome measures for the hand and wrist. The measures are aligned to the Body Functions and Activities and Participation chapters of the International Classification of Functioning Disability and Health (Cieza et al., 2005; Schiariti and Masse, 2014). To this aim, a randomized, multiple-baseline, single-case experimental design with two phases was applied (pre-post intervention) with the same population of 19 youth with CP previously described (see Figure 1.17).

- During Phase 1, participants met once with the researcher and occupational therapist in clinic. In a Solution-focused Coaching style conversation, they discussed: motivations for participating, personalized scheduling and practice goals, how the intervention connects to daily activities. By the end of this conversation, participants established Canadian Occupational Performance Measure goals (Law et al., 1990). The dialogue was intended to improve cognitive engagement and consequently, home-play adherence (McPherson et al., 2018).
- During Phase 2, a therapist assessed bimanual performance (Assisting Hand Assessment) and gross manual dexterity (Box and Blocks). The researcher visited each participant's home for multiple baseline testing of wrist extension and grip strength (3–6 visits, 30-minutes sessions). The number of baseline sessions was 'data-driven' to establish stability in the

primary measure of effectiveness: active wrist extension–open fingers. After baseline, participants waited a computer-generated randomized number of days (between 1–10 days) to begin the intervention. During these two baseline sessions the researcher habituated the participant to learn to control the video game using a therapeutic gesture, one of: wrist extension- open fingers, wrist extension- closed fingers, finger-thumb pinch, supination. Therapists helped participants identify which gesture to practice based on the daily activities that were established to be important to them.

- After the randomized waiting period, the researcher gave participants the system to practice at home. The system includes hardware: laptop, electromyography (EMG) and inertial sensor (Myo Armband) and software: adapted commercial video game (Dashy Square) and custom software to interpret movements and control the game (MATLAB 2017b). Participants practiced at home alone for 4-weeks according to their self-defined practice schedule established during the initial conversation. Once per week, the researcher visited each participant during 60 min. During this visit, he recorded gameplay with a video camera (see True Labels in Macintosh et al. 2021), he measured wrist extension and grip strength, and he had a 'check-in' conversation to re-evaluate the self-defined practice goals.
- Within 2-weeks following the final visit, participants returned to clinic for a 60-minute assessment with the researcher and occupational therapist. The therapist re-evaluated: bimanual performance (Assisting Hand Assessment), gross manual dexterity (Box and Blocks), and Canadian Occupational Performance Measure goals. The researcher conducted a semi-structured interview to gain participant's subjective evaluations of the intervention. Finally, a separate member of the research team (other than who completed the home visits) made a (5–10 minute) telephone call with participant's caregiver. The researcher asked questions and noted responses related to system use and integration into home-life.

To address *process feasibility*, *a priori* success criteria were compared to observed outcomes. According to these criteria, the study was then given one of the following recommendations: Not feasible, Feasible with minor modifications, Feasible with close monitoring, Feasible as is according to criteria set by Thabane et al. 2010. Concerning *scientific feasibility*, the size and variance of the effect of the intervention on participant-centred outcome measures were evaluated. As no single measure covers all aspects of function and experience during home-based interventions, complementary measures are used to capture changes:

- Measures for Body Function, changes in:
  - active wrist extension–open fingers. A manual goniometric measurement of active wrist extension with open and closed fingers was made.

- grip strength. A modified sphygmomanometer was employed to evaluate relative changes in grip capacity.
- gross manual dexterity measured by the Box and Blocks test.

- Measures for Activities and Participation, changes in:
  - functional bimanual performance measured through the Assisting Hand Assessment which quantifies spontaneous functional bimanual performance.
  - perceived functional performance in a self-identified goal evaluated through the Canadian Occupational Performance Measure.
  - perception of meaningful participation experiences estimated with the Self-Reported Experiences of Activity Settings questionnaire (four domains: personal growth, psychological engagement, meaningful interactions, choice and control) (King et al., 2014).

Table 1.1 summarizes the a priori success criteria evaluation for the *process feasibility* evaluation. As most (*i.e.* recruitment rate, completion), but not all criteria (*i.e.* frequency of technical issues) were met, the recommendation is 'feasible with minor modifications'. Main results concerning *scientific feasibility* showed that there was a moderate to large effect for active wrist extension. Grip strength also increased with a small to moderate effect. A positive increase in at least one Body Function measure was seen in 14/19 participants. Change score for non-dominant Box & Blocks performance showed a moderate effect. Four weeks of the intervention showed a small effect in Assisting Hand Assessment score. There was a moderate effect for Canadian Occupational Performance Measure performance scores. The Self-Reported Experiences of Activity Settings questionnaire showed participants felt positively about the activity at the beginning and end of the intervention event though this score did not change. Most but not all *a priori* success criteria were met, as such the intervention approach is *feasible with modifications*, most notably in the refinement of the technology to mitigate technical issues. Clinical outcomes of the intervention were promising with moderate effects in Body Function measures and small-to-moderate effects in Activities and Participation measures.

Criteria	Percent achieved	Evaluation description	Criteria met
≥10% response rate	31%	19/62 of eligible participants were recruited	Yes
≥80% complete study	84%	3/19 participants completed all assessments	Yes
≥66% of the self-identified practice goals met	74%	14/19 participants met goal criteria*	Partial
0 practice restrictions from technical issues	17%	6/36 reported technical issues not resolved immediately and restricting practice	No

* Partial completion as some but not all participants (74%) reached ≥66% of the self-identified practice goals.

Table 1.1: Feasibility success criteria evaluation (from MacIntosh, Desailly, et al. 2020).

To conclude, this multidisciplinary project has been conducted on two continents, thanks to an

unfailing commitment from the PhD student, Alexander MacIntosh[5]. Among all contributions associated to this project, we may cite the comprehensive evaluation of the quality of evidence of biofeedback interventions aimed at improving motor activities in people with CP, as well as the identification of important yet underused biofeedback characteristics to consider when designing motor rehabilitation activities. This work permitted to establish an infographic for wide audience to serve multi-disciplinary teams building technologies that practice motor activities. This offers one of the few tangible examples of how to implement biofeedback into a motor intervention. The software developed through this project is open-source, thus helping researchers and developers process muscle activity and inertial measurements into usable biofeedback and game controls, available on GitHub. The feasibility study showed how a home-based protocol may supplement traditional manual therapy using biofeedback-enhanced serious game (and Solution-Focused Coaching style support structures). Finally, this protocol did directly benefit some participants with manual function and ability in order to perform daily activities. This system is now available for clinicians at Fondation Poidatz and Holland Bloorview Kids Rehabilitation Hospital.

In this section, on-body sensors have been used to provide either a real-time ergonomic feedback (Vignais, Miezal, et al., 2013), or CP-specific biofeedback elements (MacIntosh, Vignais, Vigneron, et al., 2022). This may be considered as specific real-time interventions, *i.e.* actions aimed at modifying task content in order to augment task performance, reduce the risk of MSDs, and/or improve user's well-being (Lim and D'Souza, 2020). However, providing visual biofeedback elements through augmented or virtual solutions may be time-consuming and hard to implement. Another way to help a person achieving a motor action is to directly assist her/his movement at joint level with a physical disposal, as permitted by exoskeletons.

The story behind

The first time I met Alexander MacIntosh, he was a Master student at McMaster University and I was a postdoctoral fellow. After a successful collaboration on one of his Master project (MacIntosh, Vignais, Cocchiarella, et al., 2014), we became friends and we kept in touch after I went back to France in 2014. So it was a great surprise when he called me one year later to ask if I would acept to supervise him as a PhD student! Setting up this cotutelle doctoral project was probably one my harder administrative challenge. But Vincent, Eric and Elaine have always been a great support for that project. And Alexander obtained several scolarships, which clearly simplified the process (Eiffel fellow, Schmidt Science fellow, etc.). Usually science objectives are leading the way to conduct research. In that case I have to admit that it was half science and half friendship... and it was such a pleasure to go back to Canada in 2019 for his defense.

[5] Alexander MacIntosh is now Research Manager and Scientist at Altus Assessments company (Toronto, ON, Canada).

1.4 Evaluation of the Human-Exoskeleton Interaction

Different strategies may be settled to prevent MSDs (1.1.3). Among them, the primary prevention strategy includes technical/ergonomic interventions. This kind of intervention at the workplace aims to reduce the physical workload and thus decrease the risk of MSDs in workers. It can imply mechanisation of a process, redesign of a workplace, ergonomic work equipment, protective equipment and exoskeleton (EASHW, 2008). Indeed, exoskeletons are wearable devices that may enhance or support the physical capacity of the user, thus appearing as a promising tool to prevent MSDs (Muramatsu et al., 2011; Sylla et al., 2014; Theurel, Desbrosses, et al., 2018; Xiloyannis et al., 2019). However, The implementation of these devices can lead to new risks and shift the physical load to other regions of the body, or it can limit the comfort of the user as well as his freedom of movement (Peters and Wischniewski, 2019; Theurel and Desbrosses, 2019). It is therefore necessary to understand what are key elements of the human-exoskeleton interaction (HEI) before applying this disposal in the field of ergonomics.

The term *exoskeleton* comes from biology where it refers to an external articulated rigid structure which protects multiple invertebrates. This term has been borrowed for technological purposes (Yang, Zhang, et al., 2008). In the current manuscript, an *exoskeleton* will be defined as a mechanical or/and robotic device which assists human through a motor action. As an analogy with its biological counterpart, an exoskeleton can: transmit efforts through a support, increase force through motors or storing/recovering energy systems, protect the user by a role of shell or by decreasing constraints applied on joints and muscles, provide supplemental sensorial information through sensors. Thus, an exoskeleton is composed of rigid and articulated parts, worn by its user (INRS, 2020a). This feature implies that efforts produced by the exoskeleton are applied not only at the end-effector, *e.g.* the hand, but also at segmental level. Exoskeletons have been developed and designed in order to increase motor abilities of a valid individual, or to reinforce/restore motor abilities of a disabled person (Bogue, 2015; de Looze et al., 2016; Gopura et al., 2011). Thus an exoskeleton may be defined as "a mechanical support disposal, composed of articulated rigid parts, which aims to work in symbiosis with the user by providing a adapted physical assistance" (S. Bastide, 2021).

Exoskeletons may be classified according to the fact they are actuated (*e.g.* active, robotized, powered), or non-actuated (*e.g.* passive, unrobotized, unpowered). In the current manuscript, the terms *active* or *passive* will be used to describe exoskeletons. Passive exoskeletons are equipped with spring structures that permit to store and restore mechanical energy. They are designed to restore this energy during awkward posture and movements that may induce MSDs, usually for the back and upper limbs. Thus most of them have been conceived for occupational applications. They are usually limited to load lifting or posture sustaining by providing a support at back or shoulder levels (de Looze et al., 2016; Theurel and Desbrosses, 2019). Active exoskeletons are

more versatile as they are motorized and thus able to product joint-independent torques. These torques are commanded by control law that may be adapted to the specificity of the task. This kind of exoskeleton may therefore be applied to partial or full assistance in motor rehabilitation (Pirondini et al., 2016). Exoskeletons may also be categorized according to the body parts they are assisting (S. Bastide, 2021). In the current section and future research projects, passive and active exoskeletons dedicated to the upper limbs will be tackled.

As a MSDs prevention strategy, an exoskeleton has to be able to follow the human movement while compensating efforts to relieve joints and muscles during motion. The ability of an exoskeleton to follow the human movement without perturbation is called *transparency*. This critical component of the HEI will be further analyzed through the doctoral project achieved by Simon Bastide (2017-2021) in the first part of this section. To be intuitive, an exoskeleton has to react in an efficient way, by almost anticipating user's future actions. This would mean that the command of the exoskeleton might be based on a *bioinspired control law.* This investigation will be addressed in the second part of this section, based on the doctoral project from Benjamin Treussart (2017-2021).

1.4.1 Development and evaluation of a transparent control law in HEI

When lifting a tool in an occupational situation, the exoskeleton has to counterbalance weight and inertia of the tool while leaving whole motion control to the worker. Thus the worker may freely achieved the task in a little-effort way. This transparent mode of control aims not to modify joint trajectories, end-effector trajectories and user's activation muscle patterns (Jarrassfffd, Tagliabue, et al., 2010; Lamy et al., 2009; Pirondini et al., 2016). Theoretically, a full transparency is obtained when interaction forces between exoskeleton and user are null. Practically, this full transparency is never reached due to the multiple parameters characterizing HEI, thus we called them 'quasi-transparent' or 'as transparent as possible' mode of control. Some factors are currently limiting transparency in HEI, as poor dynamic identification, joint misalignment or unadapted control law. A fundamental limit is also related to the fact that the exoskeleton can not compensate its own dynamics in real time without *a priori* knowledge about the intention of the movement, uncompensated inertia thus creating unintended interaction forces through acceleration of the robot segments (Colgate and Hogan, 1989; Geffard et al., 2000). Subsequently, even in a 'as transparent as possible' mode of control, human motor control may be modified through joint coordination (Jarrassfffd, Tagliabue, et al., 2010), muscle coordination (Pirondini et al., 2016), and en-effector kinematics (Jarrassfffd, Robertson, et al., 2008). Understanding human motor control when interacting with an exoskeleton appears as a critical factor for the development and enhancement of HEI (Ajoudani et al., 2018; Frisoli, 2018; Lee et al., 2012). Thus the aim of this project was to: (i) analyze the influence of transparent control law on HEI, and (ii) improving

transparency of the HEI on the basis these preliminary results.

1.4.1.1 Influence of transparency on HEI

The transparent mode of control has to be considered as an initial mode of control, before any development in the command of the exoskeleton, as a perturbation observed in this mode will irremediably induce larger perturbations in other modes of control. Analyzing its influence on HEI appears a prerequisite for further developments on an exoskeleton. To accurately investigate this influence, simple elbow flexion/extension movements have been analyzed, on the basis of the motor control knowledge for this paradigm (Berret and Jean, 2016; Gaveau et al., 2016). The ABLE exoskeleton was used for these investigations (see Figure 1.18). This upper-limb exoskeleton may be qualified as *reversible*, meaning it is able to be 'as transparent as possible' or to apply torques for assisting movement, according to the task (Garrec, 2010). The control law natively implemented into the ABLE exoskeleton is based on a closed-loop position control. The set value for position θ_c is obtained by estimating position of the robot $\theta_r$at the next iteration on the basis of the velocity obtained through derivation of the position measured by encoders. This method allows the robot to follow user's movements. Sampling rate associated to the controller is equal to 1kHz. The position control is combined with a compensation of viscous frictions $v\dot{\theta}_r$, dry frictions τ_{sec} and gravitational torques $G(\theta_r)$ of the robot. Thus force torque τ_r produced by the robot to compensate for its own dynamics at elbow level may be expressed as follow:

$$\tau_r = \hat{v_r}\ \hat{\dot{\theta}_r} + \hat{\tau}_{sec} + \hat{m_r} g \hat{l_r} \cos(\hat{\theta_r}) \tag{1.1}$$

where $\hat{v_r}$,$\hat{m_r}$,$\hat{l_r}$ are estimated values for viscosity coefficient, mass of the robot, and distance between joint centre and COM of the robot forearm, respectively. This control law allows the robot to compensate for its own weight and its frictions. However, its inertia is not taken into account in this law. Thus inertia of the exoskeleton should be felt by the human during interaction given the fact that both forearms, *i.e.* robot and human, are attached. They may be modeled as follow:

$$\begin{cases} J\ddot{\theta_h} + v_h\dot{\theta_h} + m_h g l_h \cos\theta_h = \tau_h + \tau_i \\ J_r\ddot{\theta_r} + v_r\dot{\theta_r} + \tau_{sec} + m_r g l_r \cos\theta_r = \tau_r - \tau_i \end{cases} \tag{1.2}$$

where τ_i represents the interaction torque, J is the moment of inertia with respect to elbow rotation axis. h and r indices correspond to similar quantities related to human and robot, respectively. Interaction torqueτ_i may be estimated by replacing τ_r from equation 1.2 by its expression in

equation 1.1. Thus, if we consider that estimated parameters in equation 1.1 are known, interaction torque may be reduced to:

$$\tau_i \approx -J_r\ddot{\theta_r} \tag{1.3}$$

Moreover, by making the assumption that joint angles from human and robot have equal accelerations ($\ddot{\theta_r} = \ddot{\theta_h} = \ddot{\theta}$), the equation for the human forearm motion is simplified and may be expressed as:

$$(J_h + J_r)\ddot{\theta} = \tau_h + v_h\dot{\theta} + m_h g l_h \cos\theta_h \tag{1.4}$$

These equations permit to show that during the HEI with this control law, there is an increase of inertia felt by the user. This is not a trivial situation as it is quite rare to separate gravitational torque ($mgl\cos\theta$) and inertial torque ($J\ddot{\theta}$) in everyday life situations. Consequently adaptation to this control law might be longer than a typical load carrying task. However, this may also be considered as a parametric learning situation, per opposition to a structural learning situation (Ingram et al., 2011; Wolpert and Flanagan, 2010). This would mean that whole structure of the dynamics is conserved and inertial parameters just need to be updated. Thus it can be suggested that the adaptation to an additional inertia will be performed in a fast manner, on the basis of a parametric learning situation. This adaptation process may be separated in two phases: *transitional*, *i.e.* modification process of the motor behavior, and *permanent*, *i.e.* final behavior reached. Both regimes wil be investigated.

All investigations were conducted on a 1-DOF pointing task. Participants were asked to perform elbow flexion/extension movements in a sagittal plane. Firstly, the upper limb was immobile along the trunk. Then participants had to perform movements according to different targets in front of them. Target reaching was based on a 'one-shot movement' trial. An upward movement was always followed with a downward movement. A 1-to-2-sec break was given between targets. A goniometer was first used to measure elbow kinematics, and EMG sensors were recorded on biceps brachialis, brachioradialis, triceps brachialis (long and lateral heads) muscles (see Figure 1.18).

Transparency and additional inertia: transitional regime 21 right-handed participants took part to this study (Bastide et al., 2019a; Bastide et al., 2019b). The participant was asked to perform elbow flexion/extension in a vertical plane towards two lighted targets (+30 and -30° around horizontal axis). It was necessary to stabilize on the target before it turned off (target stayed lighted on during 1 sec). There was no familiarization phase with the exoskeleton, first trials

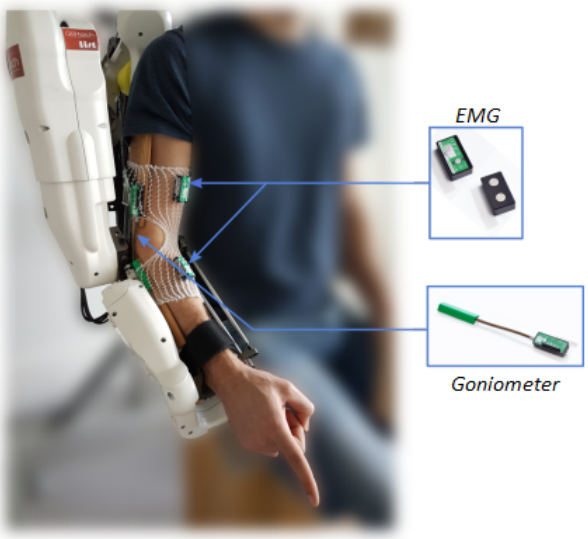


Figure 1.18: ABLE exoskeleton (1st version) for HEI analysis with goniometer and EMG sensors (Biometrics Ltd, Newport, UK) (from S. Bastide, 2021).

being the first interactions with an exoskeleton for all participants. 50 upward and 50 downward movements were performed. Kinematical and muscle activity data were analyzed as described in S. Bastide (2021). A 95% confidence interval on the last 40 movements was used to define the number of trials necessary to adapt. Results showed that movement duration of the three first flexion movements were above the confidence interval both for upward and downward movements. Mean velocity and acceleration peak were also significantly different for the first three trials. The first movement was widely different from the others, being 200 ms longer in average, with an important overshoot in comparison to the other trials. Muscle activity analysis showed that agonist muscles followed a similar trend, muscle activity of the agonists being under the confident interval for the first trial only. Thus six complete movements, *i.e.* three flexions and three extensions, appear necessary to adapt to the new dynamics induced by the exoskeleton. The weak muscle activity combined with a increase of movement duration on the first trial demonstrated that participants underestimated additional inertia provided by HEI. This was confirmed by the overshoot measured for the first movement, meaning that participants were not able to brake the exoskeleton with this additional inertia. This adaptation appeared slower than when interacting with a unknown mass, a situation for which participants were able to estimate the mass before moving thanks to gravitational torque when it was placed into the hand (Bock, 1990). Only few movements were necessary to adapt to HEI, confirming the parametric learning hypothesis when interacting with an exoskeleton.

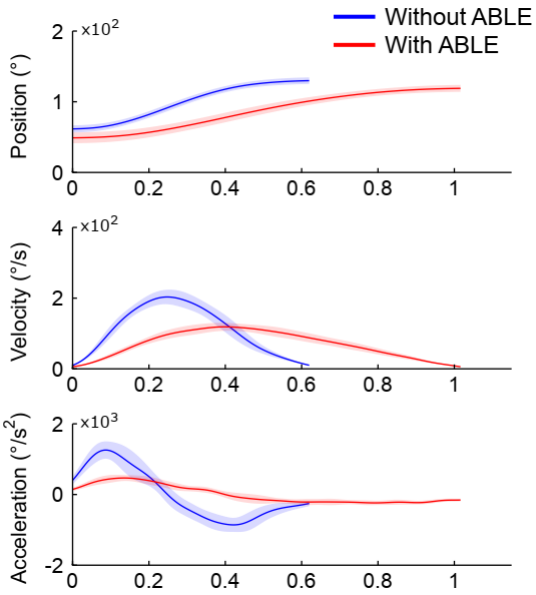


Figure 1.19: Temporal evolution of kinematical variables for a 60° upward movement. Solid lines represent the mean of 10 trials (± standard deviation in shaded areas) performed by a representative participant (from (Bastide et al., 2018)).

Transparency and additional inertia: permanent regime We recruited 18 right-handed participants for this study. They had a familiarization phase with the exoskeleton before the experiment. Then they had to perform elbow flexion/extension movements in the vertical plane on five different targets, inducing amplitude motion of 20, 40, 60, 80 and 100°. Participants also had to perform the same tasks without the exoskeleton in order to define reference movements. For each situation, 10 repetitions were performed, resulting in 200 movements in total (5 amplitudes × 2 directions × 2 with/without exoskeleton × 10 repetitions). Contrary to the previous experiment, participants did not have any time constraint to do the task, they were asked to do it as naturally as possible. Kinematics and muscle activity have been analyzed based on the same process than previously. An additional inverse dynamics analysis has been performed based on 1.4. For each participant, absolute work was calculated, *i.e.* absolute value of mechanical power at elbow level, as well as integral of squared elbow net torque, which may be associated to an estimation of the energy expenditure linked to the loss of thermal energy (Nishii and Murakami, 2002). Results showed a decrease in velocity and acceleration when wearing the exoskeleton. This phenomenon is associated to a significant increase in movement duration (see Figure 1.19).

Amplitude/velocity linear relationship was also affected by the HEI. Linear regressions showed that the slope was significantly lower when interacting with an exoskeleton for both directions of movement. On average, mean velocity is 30% higher without the exoskeleton. However,

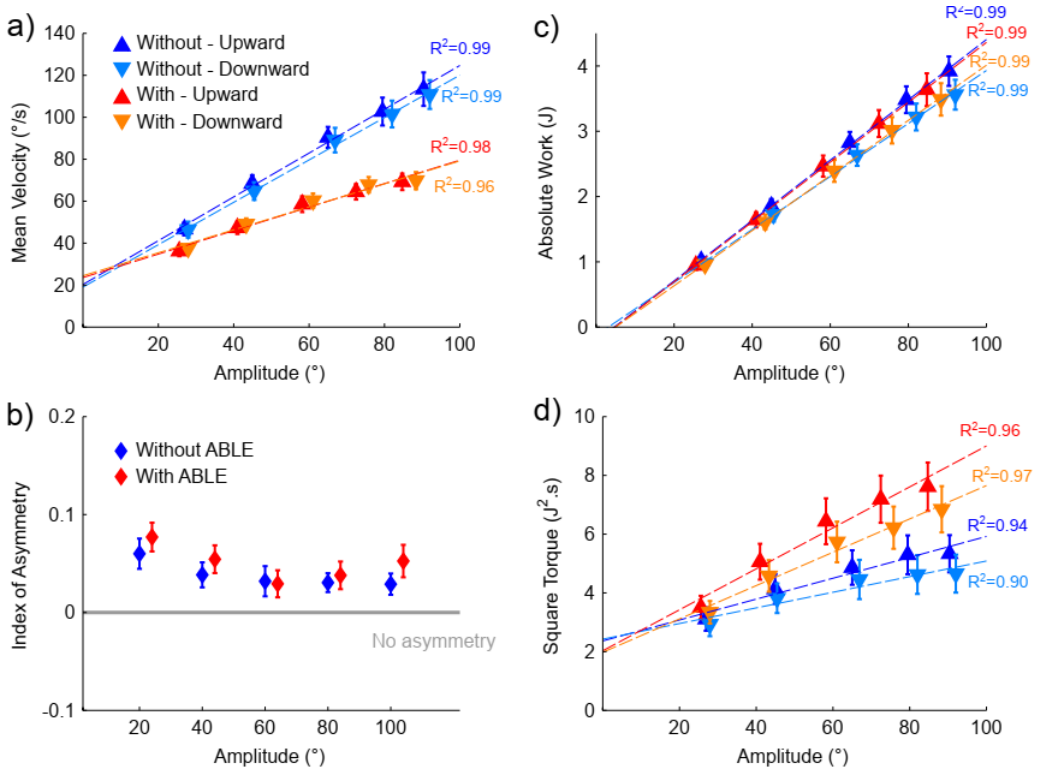


Figure 1.20: Angular velocity (a), index of asymmetry (b), absolute work (c) and square torque (d) depicted as a function of movement amplitudes averaged for all participants (± standard deviation). Dotted lines represent linear regressions with associated coefficients of determination (from Bastide et al., 2018).

determination coefficients appeared high with and without the exoskeleton. This would mean that the linear relationships relating amplitude to velocity was not impacted during HEI. Directional asymmetries confirmed that idea as they did not show any significant difference between the two conditions (see Figure 1.20). There was no significant difference between slopes of amplitude/work relationships, although we would have expected an increase of absolute work due to the additional inertia related to the exoskeleton. This may be explained by the decrease in movement duration which would have compensated this theoretical higher inertial torque. Square torque showed that moving with an exoskeleton implied a significantly higher quantity of energy, with higher values obtained for upward movements.

Results demonstrated that the ABLE exoskeleton was not fully transparent and altered even simple elbow flexion/extension movements. This is in accordance with previous studies using the same robotic device (Jarrassfffd, Robertson, et al., 2008; Jarrassfffd, Tagliabue, et al., 2010). The time to perform the task was significantly higher when wearing the exoskeleton and this difference increased

substantially with motion extent. As a consequence, an overall movement slowness occurred, even for a simple elbow flexion/extension motion. This impact might have important consequences in terms of productivity and/or acceptability, in industrial or rehabilitation contexts. Our theoretical considerations nevertheless suggested that this phenomenon could be due to the additional inertia induced by the exoskeleton (Bock, 1990). Besides this major change in movement speed, several results are encouraging and show that interacting with ABLE did not break well-known motor principles. First, the "isochrony principle" was conserved in presence of the exoskeleton (although it was qualitatively changed), which indicated that the brain still increased speed as a function of distance (almost in an affine way for the range of amplitudes tested, except maybe for the larger amplitudes). Second, the typical up/down asymmetry of velocity profiles was found to remain the same. This outcome is consistent with the fact that the exoskeleton did not modify gravitational torque, asymmetries being a signature of gravity use in movement planning (Gaveau et al., 2016). This could make sense as wearing the exoskeleton does not modify the weight of the human limb. This latter result may be seen as a proof of efficiency of the exoskeleton gravity compensation controller. As both fundamental laws considered here have been mainly conserved, our findings suggest that the kinematic properties of human movement were mainly re-scaled instead of completely altered in presence of the exoskeleton. From an energetic point of view, a trade-off seemed to appear between the increase of inertia due to ABLE and the decrease of velocity when wearing ABLE. On the one hand, additional inertia should increase the work and amount of dynamic torque. On the other hand, a reduction of velocity would decrease dynamic torque. Gravitational torque is particular in the sense that its work just depends on initial/final positions whereas acting against gravity nevertheless costs energy dissipated as heat. While wearing ABLE did not imply an increase of joint power on the human side, it still implied a greater total amount of integrated squared torque especially for large amplitudes. Thus moving with an exoskeleton controlled in transparent mode has an impact on human motor control, but this impact may be predicted as motor control principles appear sustained during HEI. Differences were mostly due to the additional inertia which was not compensated during the movement of the exoskeleton. But some ideas exist to make this control law 'as transparent as possible'.

1.4.1.2 Improving transparency for HEI

Based on the two previous experiments, it may be suggested that a better compensation of the additional inertia induced by the exoskeleton would increase the transparency of the robot. Moreover, an accurate quantification of inherent parameters which compose the exoskeleton dynamics might decrease negative impacts on human movement. These hypotheses may be tested through an augmented platform for HEI investigation into the CIAMS laboratory (see Figure 1.21).

In this platform, the exoskeleton has been improved with a slider that enables the robot to follow the human forearm without creating hyperstatism problems. Moreover, this passive degree of freedom permits to reduce constraints due to joint misalignment (Verdel, Sahm, et al., 2022).

In this study, an identification method has been added to improve parameter estimation for exoskeleton dynamics. Details about this method can be found in Verdel, Bastide, Vignais, et al., 2021. It has to be noted that this identification procedure permitted to differentiate the robot dynamics for upward and downward movements. Moreover, it allowed an accurate estimation of the position of the slider (this position being able to impact dynamics of the exoskeleton). This process permitted to design two new control laws. In total four conditions were tested:

- a reference condition which corresponded to pointing tasks without exoskeleton (*Ctrl*)
- a condition with the native control law (see previous study) in closed-loop control (*CLPos*)
- two conditions with an open-loop control. These two control laws were fully based on dynamic compensation of the robot, with mechanical parameters accurately identified during the specific procedure described in Verdel, Bastide, Vignais, et al., 2021. Moreover, inertial torque of the robot was estimated and applied to velocity, on the basis of a predictive model, in order to better compensate the additional inertia. The first of this two control laws did not fully compensate for friction, the aim being to test the effect of a partial dynamics compensation paradigm (*PC* for partial compensation). The last control law completely compensate for dynamics of the exoskeleton (*FC* for full compensation). The impact of these innovative control laws on human motor control has been investigated through relevant motor control indices.

Six young healthy right-handed participants were tested on elbow flexion/extension movements during pointing tasks with a locked wrist joint (through an orthosis). EMG sensors were placed on biceps, triceps and brachioradialis. Kinematical data were also collected through an optoelectronic system. Pointing tasks were performed on a sagittal plane, with targets displayed on a projection screen placed in front of the participant. A virtual pointer represented the projection of the forearm-index line on the screen. The trial was considered as successful if the participant was able to place the pointer on the target during 2 sec. The initial position was -30° with respect to the horizontal axis. Five amplitudes were examined: 12, 24, 36, 48 and 60° for each of the condition described in the previous paragraph. Each participant had thus to perform 400 movements (5 amplitudes × 2 directions × 4 conditions × 10 repetitions). A short break was given every 50 movements.

A new index was also created to better assess the transparency of the exoskeleton. Indeed, none of the existing index permitted to relate the motor command at the origin of the movement and the resulting acceleration of the human forearm, even though it is a critical point to assess the

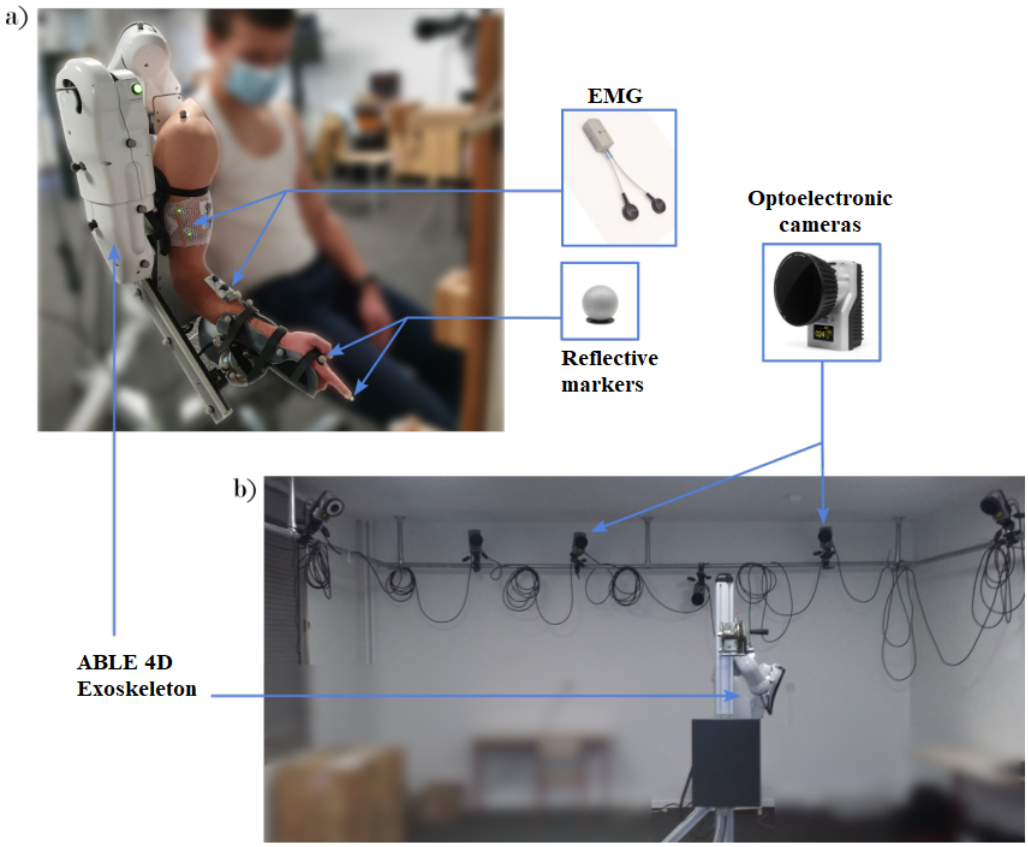


Figure 1.21: Platform for HEI analysis into the CIAMS laboratory composed of an optoelectronic system (Qualisys, Göteborg, Sweden), and EMG sensors (from S. Bastide, 2021).

transparency. Indeed, it is important to know how the wearing of the exoskeleton impacts the ratio conversion between these two variables, a high correlation existing between acceleration duration phase and agonist muscle burst duration for forearm flexion and extension (Cooke and Brown, 1990; Cooke and Brown, 1994). An EMG-based transparency index is thus defined as the ratio between the agonists RMS activation and the maximal acceleration during the movement phase. We then subtracted and normalised the obtained value with the control condition value (without exoskeleton). A value equal to zero reflects that the RMS activation of agonists muscles create the same acceleration than without exoskeleton. This index is called "EMG/Acc" and was expressed as:

$$EMG/Acc = \frac{1}{C}\left(\frac{A_{agonist,RMS}}{\ddot{q}_{elbow,max}}\right) - 1 \tag{1.5}$$

where $A_{agonist,RMS}$is the mean RMS activation of the agonist muscles (here the biceps and brachioradialis), $\ddot{q}_{elbow,max}$ is the maximal angular acceleration of the elbow and C is the ratio obtained with the control condition (without exoskeleton). This index was not computed for downward movements because of the gravity working in the same direction as the agonists muscle.

Results about kinematics showed that the global profile of vertical arm movements, as previously observed, was preserved when wearing the exoskeleton (see Figure 1.22a). Average durations of all movements (all amplitudes and participants pooled together) have been compared through the control laws. The PCFr and CLPC control laws significantly affected the execution duration in comparison to the two other laws. Conversely, the FC law had no significant impact, confirming that the duration of the whole movement can be a good first-sight performance index to estimate the achieved level of transparency (Jarrassfffd, Tagliabue, et al., 2010). Peak of velocity showed that FC law had a lower impact on the human movement than the two other laws, because there was no significant difference between this condition and the Ctrl condition, as opposed to the PCFr and CLPC conditions. The isochrony principle was conserved for the three control laws. The EMG/Acc index showed an improvement of the muscular activation/acceleration yield with the use of the FC law compared to the two other laws (see Figure 1.22b), the CLPC law appearing as the least transparent law according to this index.

These results demonstrated that with the FC law, participants were more likely to produce a greater acceleration with the same amount of muscular activation than with the CLPC law. This supports the fact that the EMG/Acc index may be used to express the level of transparency of a control law, and probably easier to settle for a task with one DOF. Indeed, processing a large number of agonist muscles acting on multiple joints simultaneously might appear complex. Muscle synergies might help in that kind of signal process (Delis, Panzeri, et al., 2014). This study overall confirmed that the

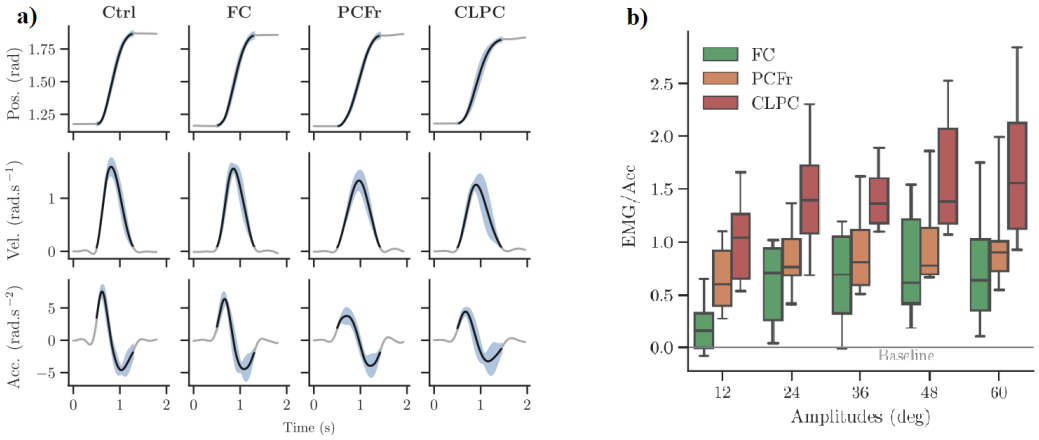


Figure 1.22: Representative trajectories of position, velocity and acceleration across time for one participant (a), and mean agonist muscle transparency index for upward movements (from S. Bastide, 2021; Verdel, Bastide, Vignais, et al., 2021). Ctrl: Control condition without wearing the exoskeleton. FC: Full compensation based on identification. PCFr: Partial Compensation based on identification without Friction compensation. CLPC: Closed-loop position control.

implemented FC law gave a better level of transparency, probably due to: (i) an upward/downward movement specific modeling, (ii) an open loop to compensate the whole dynamics of the robot, and (iii) an accurate identification of dynamic parameters through a specific calibration procedure (Verdel, Bastide, Vignais, et al., 2022).

It has to be noted that the open-loop control law approach is limited by the lack of online correction which may be implemented through a feedback loop. Indeed, transparency of the FC law mainly depends on identified parameters from the robot. If this robot dynamics is modified (*e.g.* with an additional mass or joint friction increase), the transparency will decrease and thus a less symbiotic HEI will appear... By implementing a force sensor at the interface between the human and the robot, it would be possible to add a feedback loop aiming at keeping interaction torque close to zero. On the basis of an ANR project obtained in CIAMS laboratory[6], and funding obtained through iCODE Institute[7], two force sensors have been implemented into the current platform in CIAMS laboratory. These sensors have been placed at the interface between human

[6]EXOMAN ANR-19-CE33-0009 (560kd', 2020-2024), Project leader: Bastien Berret. In collaboration with CIAMS laboratory (Université Paris-Saclay), ISIR laboratory (Sorbonne Université), LIST laboratory (CEA), LURPA laboratory (ENS Paris-Saclay) and CeRSM laboratory (Université Paris Nanterre). In that project, I am Principal Investigator of Work Package 1 dedicated to "Measuring human movement in Human/Exoskeleton Interactions".

[7]Project "Control of an Upper Limb Exoskeleton through Dynamical Data", iCODE "non-thematic" proposal (10kd', 2019/2020). This research was partially supported by the iCODE Institute, research project of the IDEX Paris-Saclay, and by the Hadamard Mathematics LabEx (LMH) through the grant number ANR-11-LABX-0056-LMH in the "Programme des Investissements d'Avenir".

and robot forearm, and between human and robot upper arm. Introducing this force sensor data into the control law seemed to improve the transparency of the HEI (Verdel, Bastide, Bruneau, et al., 2021)but further experimentations with a higher number of participants are now required to confirm this result. Moreover, attachments and passive DOF have been improved in collaboration with an orthoprosthesis company (Pommier Orthopédie, Les Ulis). These choices of expanding attachments and freeing DOF have been conducted in accordance with the literature about robotic transparency (N. Jarrassfffd and Morel, 2011; Jarrassfffd, Robertson, et al., 2008). Through an experimental procedure, we showed that this permitted to avoid hyperstatism phenomenon and improve transparency, and thus subjective comfort (Verdel, Sahm, et al., 2022).

Studies presented in this section demonstrated the importance of transparency for a symbiotic HEI, applied on a 1-DOF movement of elbow flexion/extension [8]. However, in a working environment, a higher range of motion may be necessary Moreover, it is not possible to settle all motion capture systems as previously described in a workplace. Thus to be efficient, an exoskeleton needs to be control intuitively and for specific tasks, *e.g.* carrying a load. In the next section, an intuitive control law based on an EMG armband will be implemented for a load carrying task with an upper-limb exoskeleton.

1.4.2 Development of an intuitive control law for an upper limb exoskeleton dedicated to load carrying

It has been previously mentioned that transparency was limited by the fact that, when the robot is "following" the human movement, there is a delay in the control loop because the robot is not able to anticipate the human motion intention. Moreover, in the case of direct manipulation (*e.g.* when a human is handling a load), the exoskeleton needs to apply relevant forces on the human segment in order to relieve her/his physical strain. Transparency is not enough in that case, the critical point being the way to determine what are these "relevant forces". Thus detecting human motion intention appears as a critical element in controlling an active exoskeleton at workplace. Physical and cognitive interaction methods have been developed in that aim (Lee et al., 2012). On the one hand, physical interaction methods are using current knowledge about the movement kinematics to predict the following part of the movement (Muller et al., 2020), *e.g.* a movement duration may be extrapolated from acceleration peak. These methods are easier to settle as they may use sensors directly implemented into the robot. They also look more natural because effort transmission and haptic feedback are information that can be found in everyday life situations, *e.g.*

[8] Simon Bastide belongs to the first class who followed the STAPS : IEAP Master program (2015 class). He permitted to promote this Master program as he was also the first PhD student working on HEI in the CIAMS laboratory (co-supervised with Bastien Berret and Franck Geffard). He is now Data Scientist at Akka Technologies company (Toulouse, France).

when two individuals are shaking hands (Dumora, 2014). On the other hand, cognitive methods are defined as *prospective*, meaning that they tried to obtain information about movement intention *before* the movement starts. These methods may include sensors permitting to detect muscle activity (*e.g.* mechanomyography abbreviated as MMG (Geng et al., 2012), and EMG (Bi et al., 2019)), eye tracking activity (Ishizuka et al., 2018), or cerebral activity (Benabid et al., 2019). These signals appeared quite noisy and did not permit to reconstruct the whole intended motion in the past, but innovative interactive tools have been recently introduced, especially concerning the use of EMG (*e.g.* Myo armband as in Morais et al., 2016). Moreover, EMG signals have been widely used for prosthetic or assisting arm control (Ison et al., 2015; Tavakoli et al., 2017), probably in the light of electromechanical delay, *i.e.* time interval of 50 to 100 ms between EMG signal appearance and movement start (Begovic et al., 2014). Finally, EMG signals are not only composed of motion information but they also integrate muscle stiffness and fatigue data (Artemiadis, 2012). EMG drawbacks may be related to individualization of the process, environmental conditions (*e.g.* sweat, placement), and crosstalk effect, *i.e.* it is hard to discretize individual muscle influence, most muscles being superimposed.

Using EMG signals for controlling an exoskeleton may be approached with discrete or continuous methods. A discrete method aims to discriminate states or actions (Mendez et al., 2017), whereas the objective of a continuous method is to compute a parameter continuously, with a small sampling rate, *e.g.* position or effort over time (Ryu et al., 2008). To be applied in the field, an exoskeleton-based assistance solution has to be: (i) easily and quickly deployed without specific expertise, (ii) intuitive, meaning only few training is needed, and (iii) portable in order to be adapted to multiple tasks. This type of solution should permit to compensate an unknown load for example. In this doctoral project conducted by Benjamin Treussart, a methodology to detect user's intention based on EMG signal is first developed and evaluated (Treussart, Geffard, et al., 2019). Secondly, this system is tested to control an upper limb exoskeleton in order to carry an unknown load (Treussart, Geffard, et al., 2020). Finally, the methodology is improved through the integration of an individual motor control parameter (Treussart, Caron, et al., 2021).

1.4.2.1 Development of an EMG-based methodology to control an exoskeleton: a personalized calibration

Surface EMG signal processing demonstrated reliability in estimating muscle force (Al Harrach et al., 2017), and, consequently, it may be a relevant biosignal to capture the motion intention in order to control an exoskeleton. An approach mixing continuous and discrete approaches is used to evaluate the intentions of the user, and subsequently control the exoskeleton. The current study is preliminary to torque control laws, and aims to relate user's intentions to a torque. Torque values

will be used rather than normalized EMG so that future implemented control laws will assure the same behavior for each user. Firstly a robust calibration process has to be implemented in order to design a subject-specific intuitive-to-use intention detection methodology. This calibration process has to be reliable and not time-consuming to be operational. The calibration phase will be settle to detect the intention to lift or put down a charge while wearing an upper-limb exoskeleton. Based on a low-cost EMG sensor bracelet placed around the arm (Myo armband), a subject-specific mapping procedure is implemented to discriminate motion intentions during lifting tasks with a 1-DoF upper-limb exoskeleton. The process is divided into two main parts: (i) direction estimation with an artificial neural network, and (ii) a model-based intensity prediction (see Figure 1.23).

To detect the direction of the intention, an artificial neural network was designed for a four-class classification: rest, elbow extension *i.e.* triceps activation, elbow flexion *i.e.* biceps activation, and co-contraction. The co-contraction class has been dissociated from the others and did not play a role in the discrimination of the direction of intended movement. These four classes represent the main actions at the elbow joint (1 DoF). The present approach is using time windows that were fed to an artificial neural network (Gandolla et al., 2017). A time window of 30 samples was used, or 150 ms given the sampling rate of the sensors, and it was decided not to use overlapping windows to create the database from 30- second recordings in order to reduce the risk of overfitting. Our database consisted of 800 samples for each participant. A drop-out layer was used to avoid over-fitting. To train the network, two data samples of 30 sec were recorded for each class. These recordings were used to create our training dataset and testing dataset. An average precision of 96.9±3.1% was obtained for our prediction model.

To estimate the intensity of the intention, EMG signals was first pre-processed. The rectified signals were summed from all the sensors. Although spatial information was lost through this process, the classification part took it into account. Moreover, this enabled to take advantage of the cross-talk effect which increased the measure range. Indeed, when the electrode placed right upon the muscle saturated, the ones next to it were still able to provide changes in the intensity of the muscle activation. This modified EMG signal was then filtered through a low-pass filter (Hogan, 1976). A 2-order butterworth filter with a 2 Hz cutoff frequency was chosen ,and adapted in real-time with a sliding window approach. To design a user-independent control law, a model linking torque to low-pass filter EMG was used (Ullah and Kim, 2009):

$$\tau = u^a \times e^{(c-b\times u)} \tag{1.6}$$

with τ being the modeled torque, u the EMG signal, and a,b and c muscle coefficients to be determined for the biceps and triceps from calibration.

This model was calibrated in a controlled environment. The first step was to map maximal torque

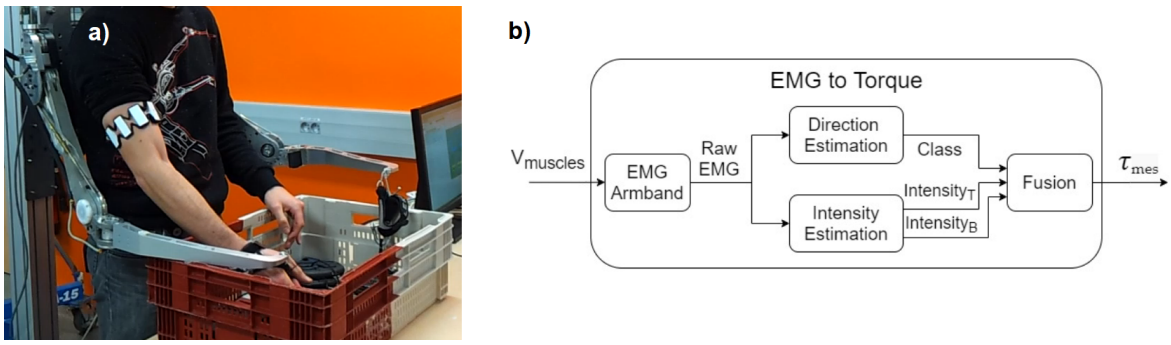


Figure 1.23: Upper-limb BHV2 exoskeleton used for the doctoral project. This exoskeleton is under-actuated and reversible. Each limb is composed of two segments and (upper arm and forearm) and four joints: two passive joints and two interrelated joints actuated with the same motor. The user is interacting with the exoskeleton at hand level with a hand strap, thus only providing upward pull force assistance (a). Approach for detecting user's intention based on direction estimation (through neural network) and intensity estimation ($Intensity_B$ and $Intensity_T$ correspond to the intensity of the Biceps activation and Triceps activation, respectively) (b) (from Treussart, Geffard, et al., 2019)

and corresponding processed EMG. To this aim, the arm of the exoskeleton was controlled with a PD-position-control law, with a high proportional gain, in order to have a stiff behavior and be in a quasi-static state. We proceeded as follow, with a rest between each step: 5 sec of biceps maximum contraction, 5 sec of triceps maximum contraction, 6 steps of 8 sec going gradually from 0 to 80% of biceps maximum contraction, 6 steps of 8 seconds going gradually from 0 to 80% of triceps maximum contraction. To get the biceps and triceps maxima, the participant grabbed the end of the arm and forced against the robot arm upward or downward. Data from the maxima of Biceps and Triceps were concatenated with their respective data from the torque step protocol. These concatenated data were used as training data for the biceps activation and triceps activation classes for the direction estimation step.

Seven participants took part to an experiment aiming at testing this calibration model. After the calibration procedure described above, each participant was asked to perform varying torques in the 2 directions, *i.e.* upward and downward, although the exoskeleton was resisting. Then fusion of the classification and intensity evaluation was conducted as follow: the classes Biceps and Triceps were used to sign the intensity, positive and negative respectively. If a rest class was detected, we assigned the value 0 to the intensity. The co-contraction condition was handled as a rest class in this version of the classification. To evaluate the model, RMS errors between torque measured by the exoskeleton and torque estimated from the current method, have been computed. They were expressed in Newton at the end-effector for reading purposes. An average error of 3.8 ±

0.8N was obtained, which may be considered as acceptable if we compare the results with (Ullauri et al., 2015), these authors obtaining an average force of 2.0 ± 0.2N. Although the current error may appear twice as important, it has to be noted that in our functional solution, we did not use a load cell for bypassing and we did not apply a precise set up for EMG electrodes. Thus this new calibration method for controlling a back-drivable exoskeleton on the basis of an EMG armband seems time-efficient and practical. It would be now interesting to explore: (i) the development of a control law based on this procedure, and (ii) the possibility of a unified classifier which would help avoid manual subject-specific adjustment (which lasts 3 min), *i.e.* a network trained on several participants which would be able to process data of new users. This would improve the time efficiency aspect of the proposed method.

1.4.2.2 Development of the control law dedicated to load carrying

We made the assumption that the worker does not know the mass of the load she/he has to lift and carry. The objective is to provide a full compensation of the load carried by the worker and worker's upper limb, thus allowing muscles to be in a relaxing state, *i.e.* a similar behavior as in a gravity compensation condition. This approach is different from a proportional-based control for which effort is reduced but muscles are still solicited. Thus a torque control loop has been developed (see Figure 1.24b), with an integral controller in order to compensate gravity and frictions, as well as reducing inertia (Geffard et al., 2000; Williams and Khatib, 1997). In the present study, this integral corrector was used to control the torque, not the one from the robot, but the one from the worker's elbow through the exoskeleton. More precisely, in this control law, the muscle relaxation objective is represented by the human elbow torque setpoint τ_{des} that was constantly set to 0. K represents the integral controller, calculated with (*intensity – threshold*) in order to have a more progressive evolution of the assisting torque. τ_{cons} was the control torque applied to the exoskeleton. F_{inter} corresponded to interaction forces between the exoskeleton and the worker. $V_{muscles}$ correspond to the myoelectric signal measured by the EMG armband. The $Dead\,Zone$ block provides a crucial adjustment parameter, allowing a more efficient use of EMGs with integral corrector (later called DZ-I corrector for Dead Zone Integral corrector). Indeed, the DZ-I corrector also has the advantage of filtering errors in the intention detection system, *e.g.* direction estimation at low and high intensity. Moreover, the threshold for the DZ-I corrector may influence the limit-cycle oscillation around null torque but also the potential static error. If the threshold of this corrector is set to a sufficient value, it may consequently allow the load to be moved without changing the assisting torque, thus yielding a behavior similar to a 'compensation of gravity' (CG) algorithm. this associated. The proposed control was tuned for and by an expert, *i.e.* someone with experience on this approach, and the resulting parameters were used for all participants.

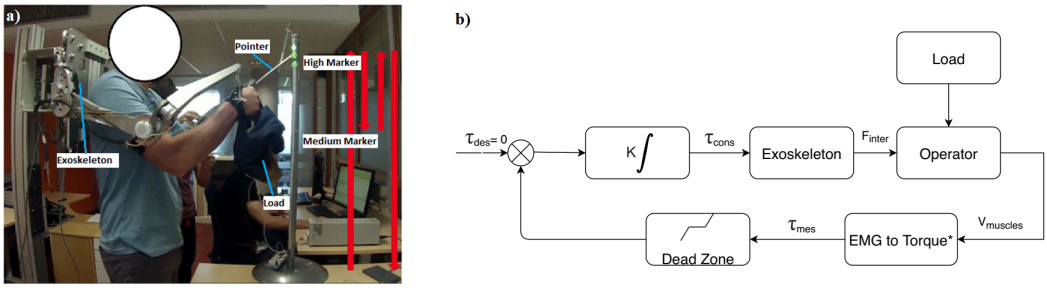


Figure 1.24: Eprimental setup (a) and control scheme for the proposed approach (* corresponds to the block in 1.23b) (from Treussart, Geffard, et al., 2020)

To evaluate the proposed control law, an experimental protocol has been conducted with 10 participants. The participant had to lift and put down a load of 5 kg repeatedly at natural speed and in three different situations : without assistance (No-Exo), with our proposed DZ-I control, and with CG algorithm control (with mass known) (see Figure 1.24a). Each participant was equipped with seven EMG sensors (DataLite, Biometrics Ltd, Newport, UK) targeting muscles relevant for biomechanical analysis during load carrying: biceps, triceps, deltoid, trapezius, erector spinae, soleus, tibialis anterior (Hermens et al., 1999). Sampling frequency was fixed to 1000Hz. These sensors were placed only on the left side, as the movement was performed in the sagittal plane, and the right arm being already equipped with the EMG armband. The processing of the raw EMG sensors followed previous recommendations (Buchanan et al., 2004; McDonald et al., 2013), a band-pass filter (bidirectionnal 7th order Butterworth [30Hz, 200Hz]) was first applied, then centered and rectified and finally low-passed. The signal was then normalized with the maximum value measured over all trials, thus defined as the relative maximum contraction (RMC). The signal was parsed and down-sampled to calculate the average muscle activation during each trial. Each participants also filled up a questionnaire for subjective analysis (Wioland et al., 2019). This questionnaire assessed how the user perceived the different situations and if her/his perception was in accordance with the objective evaluation.

Results showed a statically significant decrease in mean activity of biceps, erector spinae and deltoid by 20 ± 14%, 18 ± 12% and 25 ± 16% respectively ($p < 0.001$, $p < 0.05$, and $p < 0.001$, respectively). Previous studies from the literature also reported a decrease in muscle activation of the biceps brachii superior to 20% when using an active upper-limb exoskeleton (Aida et al., 2009; Lee et al., 2012; Muramatsu et al., 2011; Naito et al., 2007), thus reducing the physical load on the operator's shoulder and elbow during manual tasks (de Looze et al., 2016). Concerning erector spinae muscle, a reduction between 10 to 25% have been obtained during asymmetric lifting tasks with an exoskeleton (Abdoli-E and Stevenson, 2008), confirming the capacity of these devices to prevent back injuries. Although the highest decrease in muscle activation was obtained from the

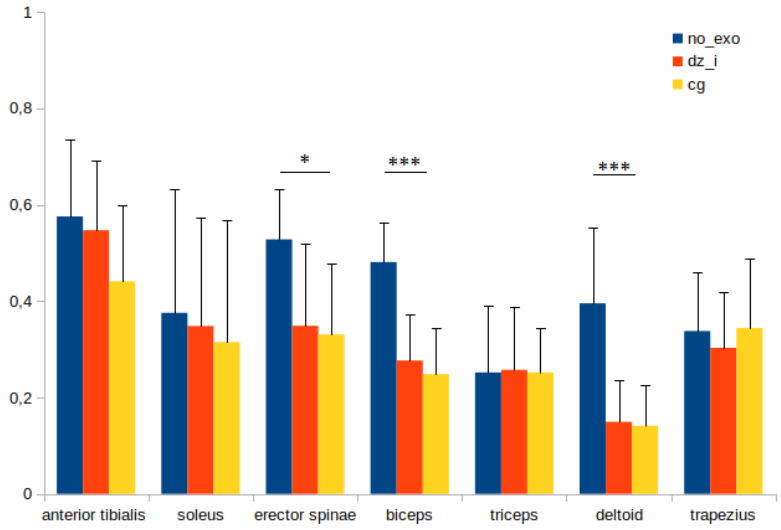


Figure 1.25: Comparison of mean muscle activations between the three conditions (*p < 0.05; ***p < 0.001) (from Treussart, Geffard, et al., 2020)

deltoid muscle, comparable values were obtained in previous studies (Muramatsu et al., 2011). Similar muscle activities were obtained for the other muscles with the proposed model and the traditional CG model. The general feedback from questionnaires was that, even though the CG control was easy to anticipate and required less concentration because of its consistency, they felt more efficient with the DZ-I control.

Concerning results about control performance, the torque of reference was defined as the torque that compensates gravity when the user was lifting the load without assistance. The average RMS error between this two torques has been calculated between the moment the load was lifted up and the moment it was put down. Mean RMS error was 0.038 ± 0.012 N.m on average, corresponding to 6.99 ± 2.27 N at the hand level. By examining the sign of this difference, it was observed that the proposed control did not systematically overshoot or undershoot in the same way for each participant, suggesting the existence of a user-specific control parameter. This parameter would influence the gain of the integrator and might be determined from the participant's reaction skills. It may also correspond to interindividual differences when discovering a new paradigm of assistance. The influence of individual reaction skills when interacting with an exoskeleton have been investigated in the last study of this doctoral project.

1.4.2.3 Improvement of the calibration procedure and personalization of the control law

The aim of this study was to adapt the EMG-based control system to a user, based on her/his individual characteristics. This would permit to adapt the gain of the K integral corrector. To this aim, a procedure has been designed to tune the parameters of control using the user's capacity to respond to a torque constraint. More precisely, we considered the user's response time as an input parameter. Response time is defined here as the lapse of time between a stimulation and the response on the EMG signal. It is different from what is usually referred to as reaction time and reflex time (Scott, 2004), reaction time being defined as the delay between a stimulus and a reaction (*e.g.* time to push the brake after spotting a pedestrian), and reflex time being the time for movement to occur after a stimulus on the muscle fibers (*e.g.* myotatic reflex). In our case the stimulation would be the increase of assistance from the exoskeleton. Our hypothesis is that the user's response time T_{resp} may influence the stability of the HEI. Personalizing the gain of the integrator K would thus ensure a safe and intuitive interaction. It has to be noted that a shorter calibration procedure was used in the current study. This new calibration procedure was based on a dataset from 20 people recorded with the previous procedure (Treussart, Geffard, et al., 2019). This dataset was then used to pretrain the neural network. Finally, the new calibration only imposed a short step of voluntary contraction of 15 seconds to calibrate the system to a new user. These data were then input into the control law to estimate direction and intensity.

To investigate the link between response time and gain of the integrator, a first step was conducted with a simulation process developed under Matlab Simulink. The system was simulated for a 1-DOF task and assimilated to a pendulum composed of a rigid arm and a load at the extremity. The user was modeled into three parts: (i) response time, representing the time it takes for the user to perceive the changes of force from the robot, (ii) central nervous system (CNS), responsible of generating the setpoint signal to perform the lifting task, and (iii) the musculoskeletal system modeled with the work from (Haeufle et al., 2014). Results were represented by a search grid with the response time and the gain as parameters. K varies from 4.5 to 8.2 with a step of 0.05 and T_{resp} from 110 ms to 210 ms with a step of 5 ms. A stability index was used to evaluate the simulation for a given pair of $[K, T_{resp}]$. More details about this simulation process may be found in Treussart (2021). This simulation step allowed to define the limiting values of the gain based on theoretical user's response times. Moreover, this procedure permitted to relate parameters from an advanced user to a new user while taking into account their differences.

Then, a procedure to measure T_{resp} has been developed in order to be further introduced into the calibration procedure. To test this procedure, five participants were asked to stay relaxed while jolts of torque were made with the exoskeleton. The jolts were triggered randomly to avoid anticipation,

and they were applied for two heights (high and low), 10 times in each direction, for a total of 40 torque jolts. EMG data were measured with the EMG armband. The objective was to find an indicator of T_{resp} that does not vary greatly between the different conditions (direction and position) but still enables to discriminate between participants. The T_{resp} computed from the three EMG electrodes placed on the biceps muscle appeared to present the least of intra and inter variability.

The last step aims to conduct an experimental protocol to evaluate the impact of a control law based on a personalized pair of parameters $[K, T_{resp}]$ on the quality of the HEI. To this aim, EMG data from 10 participants were recorded (Research protocol CER-212, Université Paris-Saclay). Two different types of EMG sensors were used in this study. The first one was the EMG armband used to control the exoskeleton based on the previous studies form this doctoral project. The armband was positioned around the arm to capture biceps and triceps muscle activities (f=200 Hz). The second one were EMG Datalite sensors (Biometrics Ltd, Newport, UK). They were used to compare exoskeleton control conditions and allow to measure muscle activities from biceps, triceps, trapezius, anterior deltoid and erector spinae at a sampling frequency of 1000 Hz. Once equipped with the exoskeleton and EMG sensors, the participant ad to perform a lifting task in different situations. Before each mode of control, *i.e.* generic (GEN) vs personalized (PERSO) gain, the participant did 20 repetitions without assistance and with a load of 2kg, as a reference situation. Then, he performed 50 repetitions with one of the two assisting modes, in a randomized order, and with a 7-kg load. The participants filled a questionnaire about the assistance after each mode, and questions of comparison between the two control modes at the end of the experimentation (Maurice et al., 2020). The task was to lift a load up to a high mark, bring it down to a middle mark, high up again and finally put the load down, as in Treussart, Geffard, et al. (2020). The reference situation allowed to start the recordings in the same conditions. The targets were displayed on a screen as well as the current angular position.

Results showed that the precision obtained with both control modes were similar, *i.e.* difference between actual and current position of the target. Concerning EMG data, they were averaged per series of 10 repetitions in order to observe evolution across time. A statistically significant reduction in mean activity is observed for both GEN and PERSO for the anterior deltoid between the first and the last series ($p < 0.05$). To see if there was a difference in the initial adaptation to the mode of control, the mean activity of the anterior deltoid was compared for the very first series of 10 repetitions of the experiment, whatever the control mode was. For five participants it was GEN control mode, and for the five others it was PERSO control mode (see Figure 1.26). This muscle activity was found significantly lower for PERSO control mode compared to GEN control mode (29.0±8.0% RMC and 37.4±9.5% RMC, respectively) ($p < 0.05$) . However, this difference was not maintain with repetitions. These results align with a previous study in which the authors showed improved performances in teleoperation through a personalized control approach (Yang,

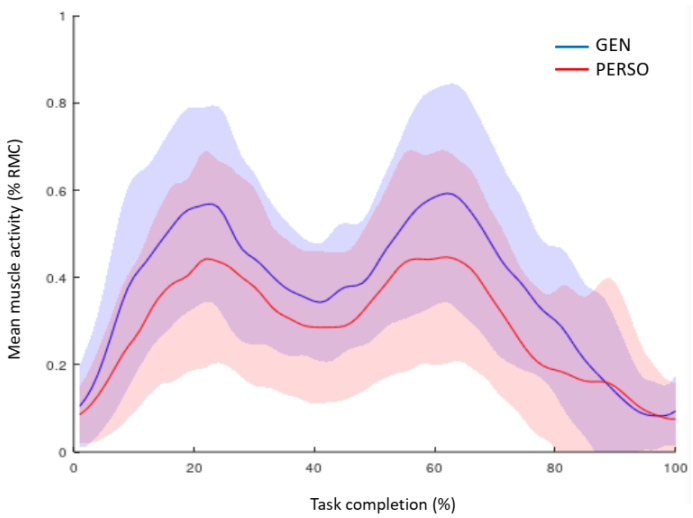


Figure 1.26: Mean muscle activity of the anterior deltoid for the very first serie of the experiment (from Treussart, Caron, et al., 2021)

Luo, et al., 2018). Authors showed that their proposed method improve performances compared to conventional approaches. In an other study Zhang and collaborators (2017) demonstrated the interest of human-in-the-loop optimization with an ankle exoskeleton (J. Zhang et al., 2017). These authors highlighted reduced metabolic energy consumption with an an personalized optimized assistance than with a generic assistance. This result is confirmed by subjective evaluation with the general question about intuitiveness in favor of PERSO control mode. Moreover, comparative questions followed a similar trend: on the two questions that significantly shifted from the neutral, one was about compared intuitiveness, favoring PERSO control mode. The second one showed that participants judged that PERSO control mode required less concentration. This last doctoral study further reinforces the fact that personalizing control mode of an exoskeleton contributes to a more intuitive system, thus optimizing the quality of HEI [9].

[9] Benjamin Treussart is now research engineer at CEA Tech (Nantes, France).

The story behind

This research topic about human-exoskeleton interactions is a funny story (at least for me!). When I obtained my assistant professor position in 2015 at Université Paris-Saclay, my lab director, Michel-Ange Amorim, asked me if I was interested in meeting a researcher from the CEA who worked on exoskeletons. I accepted and that's how I met Franck Geffard for the first time in Nano-Innov bulding. We both agreed on supervising an internship for Master 1 students (namely Benoit Gréco and Flavien Mazzon, two former graduates from Master STAPS : IEAP) about comparing spatio-temporal parameters with and without an exoskeleton. This collaboration was successful and we co-supervised Simon Bastide in 2016 for his Master 2 internship, Bastien Berret also coming "into the loop". In 2017, Simon obtained a specific Interdisciplinary PhD-project funding (IDI Paris-Saclay), one of the first proposal I wrote with Bastien (but not the last!). The same year, Franck asked me to co-supervise Benjamin Treussart with him, and he was looking for a PhD director. A perfect opportunity to work again with Pr Frédéric Marin from Université de Technologie de Compiègne! With Bastien, we then gained a 'Shared Research Equipment' funding the following year (80kd', 2018) to buy an exoskeleton for the CIAMS laboratory and for Simon's PhD work. In 2019, we kept on going with the flow through the obtention of the EXOMAN ANR project lead by Bastien. After that, Olivier Bruneau, Dorian Verdel, and now Lucas Quesada and Abdelwaheb Hafs are contributing to the EXO team. This story exemplifies the sentence "*there are more ideas in two heads than in one*" (Jacques Chirac).

1.5 Discussion

MSDs are nowadays considered as an occupational health issue, still representing 87% of occupational diseases in France in 2017 (AMELI, 2017). We showed in the first part of this chapter that physical constraints are one of the first cause of MSDs and different strategies exist to prevent the appearance of MSDs. Among these strategies, primary prevention may concentrate efforts on the risk assessment process as it is a critical elements in order to identify risk factors and thus acting on the workplace. That is what has been presented in the second part of this chapter through the use of on-body sensors for continuous ergonomic analysis. Electrogoniometers have first been employed into ergonomic assessment, both for mono- and poly-articular exposure evaluations (Besombes et al., 2019; Varraut, 2018; Vignais, Weresch, et al., 2016). IMUs have been secondly introduced, which permitted more complex biomechanical modeling and subsequently more comprehensive ergonomic assessment (Caen et al., 2018). These sensors may also be associated to a video analysis for the characterization of subtasks from an ergonomic point of view(Vignais, Bernard, et al., 2017). Even relevant, all these assessments were performed off line, although some technical solutions are existing to provide online feedback. The development and implementation of online feedback based on a human signal, also called *biofeedback*, has been presented in the third part of this chapter. Beginning by an innovative solution based on AR in the ergonomic area (Vignais, Miezal, et al., 2013), this section also dealt with a biofeedback-enhanced serious game aiming to improve hand function in youth with CP (MacIntosh, 2020). Finally ergonomic interventions based on physical assistance have been tackled in the fourth part of this chapter with the introduction of the exoskeletons. More precisely, the importance and evaluation of transparency for active exoskeletons was highlighted through S. Bastide's PhD project (S. Bastide, 2021). And the design and examination of an intuitive exoskeleton control law based on EMG was lastly presented for load carrying task applications (Treussart, 2021).

The rationale for all these previous works was based on a ergonomic conceptual framework for biomechanical exposure assessment using wearable inertial sensors (Lim and D'Souza, 2020) and adapted to more general on-body sensor network methodology (see Figure 1.4). This model integrated five different steps, *i.e. modeling, sensing, analyzing, assessing, and intervening*, and each of them may be now discussed regarding advancements conducted through the previously described research studies. In these studies, the modeling step was quite implicit, *i.e.* on-body sensors were used to obtain kinematic information to feed an ergonomic assessment (*e.g.* comfort zones for wrist, RULA table for upper body). However, biomechanical modeling step may be more explicit in ergonomic assessment, *i.e.* trying to reproduce musculoskeletal elements of an anatomical area. This kind of model may permit to fill the etiologic gap between biomechanical exposure score computation and pathomechanical process underlying MSDs. I also contributed

to this type of work by developing a musculoskeletal model of the hand and forearm with 21 segments and 26 DOF (LifeMod software) in the framework of the COGNITO European Research project (Vignais and Marin, 2014; Vignais and F. Marin, 2011). This model was dedicated to the ergonomic assessment of industrial manual tasks. Inputs of this model were real kinematical data captured by an optoelectronic system, and outputs were muscle forces and joint loads endured by the model during specific manual tasks (*e.g.* cylinder grasping task). These modeling skills were useful when supervising the development of musculoskeletal model of the hand (under OpenSim software) to analyze joint loads of the fingers with kinematical and kinetic data as inputs (Vignais, Cocchiarella, et al., 2013). Along the same lines, I also contributed to the development of a musculoskeletal model of the index (under OpenSim software) to analyze the influence of intrinsic and extrinsic muscles on finger joint loads during movement (MacIntosh, Vignais, Cocchiarella, et al., 2014)[10]. Although promising, it is somehow hard to validate musculoskeletal models. Indeed, it appears impossible to directly measure joint loads and individual muscle forces inside a specific anatomical area, especially the forearm for hand muscles... Thus researchers are more talking about "*verification*" to support the development of a musculoskeletal model (Erdemir et al., 2007; Vignais and Marin, 2014). Future challenges of musculoskeletal modeling are dealing with more detailed neuromusculoskeletal models that take uncertainty into account, and a need for tools to efficiently personalize these models (*e.g.* high density EMG) (De Groote and Falisse, 2021). When valid, these models will allow a prediction of the risk to develop MSDs through simulation *before* the design of a workplace. This approach is called *proactive* in ergonomics.

The proactive upstream approach is implemented on the basis of a digital human model (DHM) as effective ergonomics analysis and design tools, before the physical conception of the workplace, in order to reduce development costs and decrease the long-term risk of work-related MSDs (Chaffin, 2005). As a postdoctoral fellow at McMaster University, I contributed to the development of a virtual reality solution based on a DHM (Jack 8.3, Siemens PLM Software, Allen Park, MI, USA) animated through an optoelectronic motion capture system (Rizzuto et al., 2019). This study was based on a comparison of the performance obtained by participants into a real environment, and into its similar virtual counterpart. Indeed, designing a virtual environment for motor control assessment necessitates accurately recreating the perception/action loop from the operator perspective, that is, from an egocentric tridimensional viewpoint that can be updated in real-time. Moreover, a virtual environment for such applications must lead to the assumption that the virtual experience is real from the operator's subjective perspective. This subjective feeling, or 'sense of presence' (Sanchez-Vives and Slater, 2005), is not only defined by the technical capability of the hardware used, also known as 'immersion', but may be provided by a reduced technological solution adapted to the

[10]This publication was the first collaboration with Alexander MacIntosh, who I will connect again for his PhD (2016-2020)

context of use (Cummins and C. Craig, 2016). Thus, in motor control research, comparing motor behavior in real vs virtual environments may consist of a validation of the sense of presence (Bideau et al., 2003). This topic was also a continuation of research studies conducted during my PhD (2005-2009) on the development and use of a virtual reality-based methodology to analyze visual information uptake of handball goalkeepers (Vignais, Bideau, Craig, Brault, Multon, Delamarche, et al., 2009; Vignais, Bideau, Craig, Brault, Multon, and Kulpa, 2009; Vignais, Kulpa, Brault, et al., 2015; Vignais, Kulpa, Craig, and Bideau, 2010; Vignais, Kulpa, Craig, Brault, et al., 2010; Nicolas Vignais, 2009). More recently, through a collaboration with my colleague Aurore Meugnot and his former PhD student, I had the opportunity to discuss benefits of virtual reality-based solutions and the importance of using realistic movements for virtual characters interacting with real humans (Treal et al., 2021).

Concerning the *sensing* and *analyzing* components of my research, three different sensors have been mainly used: electrogoniometers, IMUs and EMG electrodes. The selection of sensor is usually based on a trade-off between the relevant ergonomic variable, the number of sensors and the worker's comfort. For example, it has been previously showed that the ankle, wrist, waist, thigh, and foot are the most preferred location for IMUs placement compared to the neck, torso, elbow, fingers (Mokhlespour Esfahani et al., 2019). Another study demonstrated sensors attached on the upper arm, hip, and back were rated relatively higher in comfort and acceptability compared to the chest location which was rated the lowest (Beeler et al., 2018). Moreover electrogoniometers and IMUs are providing kinematical information, as they are widely used as input into observational methods to assess the physical risk of exposure. It appears a lot more difficult to integrate internal parameters, *i.e.* EMG data, directly into an ergonomic assessment method. Indeed, EMG data processing is more complex and may be time-consuming. However, this is the preferential sensors when studying the impact of an ergonomic intervention based on a physical assistance (Theurel and Desbrosses, 2019). There exists some others sensors to illustrate internal parameters like MMG sensors. Although there were not initially implemented for ergonomic assessment, the technological development of MMG seems mature for this kind of applications (Correa et al., 2022). In addition to kinematical and internal information, there is a need for the integration of kinetic information into ergonomic assessment, although this kind of sensors has to be adapted directly to the environment, and thus appear less portable for ergonomic assessment (Lowe et al., 2019). Kinetic information is rather used to characterize individual parameters in terms of postural stability in biomechanics. In this respect, I had the opportunity to participate to postural control analyses for horseriders (Olivier et al., 2019). This specific population was also the heart of a national projet 'Very High Performance Sport' submitted to National Research Agency in 2019, in which I was in charge of the biomechanical analysis (on the 26 initial projects, this project has been accepted among the 10 projects for interview, but finally not funded among the six awarded projects). Into this project,

I developed a collaboration with the Centre for Nanoscience and Nanotechnology (Université Paris-Saclay) with the objective of using miniaturized pressure sensor for kinetic assessment (see section 2.2.5).

Into the previous research axes, kinematical data were processed in a simple way for ergonomic *analysis*. More precisely, the manufacturer usually provided a software allowing to directly access relevant information (*e.g.* joint angles for IMUs). In the case of EMG data, different analyses have been conducted as it is a more complex signal. An in-depth prospection about motor control variables that can be computed from raw EMG data has been conducted through A. MacIntosh PhD project (MacIntosh, 2020). Wether it was for implementing a real-time biofeedback into a serious game, or for controlling an active upper limb exoskeleton, EMG data seem to have the potential for predictive modeling (*i.e.* machine learning approach).

Ergonomic *assessment* conducted in the first part of this chapter was mainly based on the RULA method, which is widely used in the ergonomic area. Although this method allows a numerical and automatized implementation because of its joint angle basis, this method may suffer from a lack of epidemiological evidence to support the relationship between MSDs appearance and risk of exposure computation (Li and Buckle, 1999; Vignais, Miezal, et al., 2013). Some researchers are currently working on the developments on other objective measurements in order to assess the exposure-response relationships between occupational risk factors and MSDs (Nordander et al., 2016). However these types of studies have been dedicated to specific anatomical areas (neck, shoulder, forearm and/or wrist) although RULA score provided a global risk score for the whole worker's upper body, which make it simple to interpret. Moreover thresholds have to be imposed subjectively for the implementation of the continuous RULA calculation, and some prior hypotheses had also to be done to allow the RULA score computation (*e.g.* the shoulder was not raised and upper arms were not supported or the worker was not leaning during a work cycle). The selection of local scores thresholds were along the same lines. Concurrently with these calculations, the specific anatomical area of the lumbar zone, responsible for most of the MSDs around the world (Brooks, 2006), has been given little consideration through this assessment. Finally, the RULA method, even if it permitted an analysis of temporal aspects in the current study, has been initially developed to focus on static postures. Thus through this method, it was not possible to analyze the influence of the cumulative time spent at each RULA range on the risk of MSDs exposure (Svensson et al., 2010). There is thus a need to consider other assessments that may be directly related to on-body sensors for ergonomic purposes.

Finally, the ergonomic *interventions* presented in this chapter were based on online visual feedback, or on the use of assisting device controlled in real-time. In both cases, the perception/action loop between the user and the environment permits to enhance user's capacity. The central nervous

system internally simulates the behavior of the motor system in planning, controlling, and learning on the basis of the current state of the motor system and motor command (Miall and Wolpert, 1996). Thus if a new information is added into this interaction loop (*e.g.* a biofeedback, an external torque), the central nervous system will be able to integrate it to solve new computational problems in motor control. The theoretical framework of this loop supports the biocybernetical approach which aims to imply an ergonomic behavior on the basis of real-time interactions with different sensory information (on-body sensors, see-through HMD, exoskeleton) (Scerbo et al., 2000). Future research will have to consider this approach in order to optimize ergonomic interventions based on biofeedback elements. Finally, it seems that the most effective ergonomic interventions are combining actions on personal and occupational risk factors, in comparison to prevention focused only on occupational risk factors. Implementing actions of promotion of health and well-being at work would thus be necessary in addition of actions on physical risk factors (Fouquet et al., 2019).

1.6 Conclusion

All previous research works were dedicated to the prevention of MSDs. To this aim, the first step is to evaluate their risk of appearance. This step may be achieved through the use of on-body sensors, in combination with other devices. An ergonomic assessment may also be performed in real-time with an online feedback to the user, with the help of innovative solutions. Finally, an ergonomic intervention may be based on physical assistance with the use of the exoskeletons. Thus, it may be concluded that this previous research axes aimed to improve measurement and processing of relevant biomechanical parameters for an in-depth assessment of physical risk factors and the design of relevant ergonomic interventions. This objective will be continued in the next chapter on the basis of the conceptual model which incorporates modeling, sensing, analysing, assessing and intervening as major milestones for an ergonomic virtuous loop.

Chapter 2
2 Research project

THIS chapter presents my current and future research objectives. In the coming years, I plan to work on the different steps composing the conceptual framework in physical ergonomics previously presented: Modeling, Sensing, Analysis, Assessment, Intervention. Thus this research project might be untitled "Improving human motion measurement and its processing for physical ergonomic interventions". This model will be applied not only in the occupational domain, but also in the sport movement field of research.

2.1 Research objectives

This project will support my previous research with the objective of improving measurement and processing of relevant biomechanical parameters for an in-depth assessment of physical risk factors and the design of relevant ergonomic interventions. To this aim, this research project will rely on the previous physical ergonomics model (see Figure 1.4). This conceptual model is composed of five steps: Modeling, Sensing, Analysis, Assessment, Intervention. Although it may appear difficult to investigate these five steps simultaneously, there are all interconnected and the developments conducted on one of this step will impact the other steps. The first intuitive level of investigation concerns the *Sensing* step. Indeed, the enhanced miniaturization of technologies allow new biological parameters to be easily measured (see the Near-infrared spectroscopy in physiology for example). In biomechanics, some measurements like MMG deserve particular attention as they may constitute new ways of investigating risk factors during in-field situations. These measurements will represent the first axis of this research project.

Given the fact that ergonomics of physical activities aims to improve performance while preventing damages on the musculoskeletal system, this global framework may also be applied into the sport

motion area. More precisely, on-body sensors may be placed directly on the athlete during the sport situation. Data from these sensors may be analyzed to extract key factors related to the performance and/or risk of injury. The methodology may then be assessed in comparison with high-level performance and/or injury rates. Finally, once validated, this methodology would permit to propose innovative ergonomic interventions to enhance the sport performance, and above all, prevent the appearance of an injury. This application of the framework in sport biomechanics will constitute the second axis of this research program.

Although exoskeletons have been introduced in the previous chapter, their applications into in-field ergonomic interventions have not been further detailed. This is due to the fact that my previous studies focused on active exoskeletons, which may appear quite difficult to install in the field. In addition to their mass and lack of portability, motorized exoskeletons could be considerably expensive (*e.g.* the 4-DOF ABLE exoskeleton in the CIAMS laboratory costed 80kd'...). However, there exists a low-cost counterpart to these assisting devices: passive exoskeletons. As previously mentioned, a passive exoskeleton does not use any type of actuator, but rather uses materials, springs or dampers in order to store energy harvested by human motion and then to use it as required to support a posture or a motion. Moreover, these non-actuated disposals still have the potential to decrease the underlying factors associated with work-related MSDs (de Looze et al., 2016). The evaluation of passive exoskeletons (back and upper-limbs) for in-field ergonomic assessments will be introduced through a third axis of research.

Finally, in addition to passive exoskeleton applications, the control of active exoskeletons still need further investigations. Indeed, we showed that it is difficult to obtain a high level of transparency, even for simple movements of flexion/extension of the elbow. However, some measurements, like EMG data, may help detecting the intention of the user, *i.e.* being able to anticipate the coming motion right before it is produced. High density EMG is a non-invasive technique aiming to measure electrical muscle activity with closely spaced electrodes overlying a restricted anatomical area. By using these measurements to calibrate a neuromusculoskeletal model of the upper limb, an intuitive EMG-based control law may be developed and tested on movements with four DOF. Moreover, once properly controlled, the active exoskeleton may be used to guide user's movements in an ergonomic manner. These developments on an active exoskeleton and their applications will be further investigated into a fourth axis of research.

2.2 Research program

2.2.1 MMG measurements and its validation

MMG may be considered as the mechanical counterpart of EMG, being defined as the measurement of the low-frequency lateral oscillations of active muscle fibers (Beck et al., 2005). More precisely, MMG reflects three physiological phenomena: (i) the gross lateral movement of the muscle at the start of the contraction, (ii) the subsequent vibrations at the muscle's resonance frequency, and (iii) dimensional changes of active muscles fibers (Ibitoye, Hamzaid, Zuniga, and Wahab, 2014). Although different materials may permit to obtain MMG (*e.g.* piezoelectric crystals, condenser microphones, displacement lasers), accelerometers are often preferred because of their ease of fixation on the skin, their flat frequency range, their inexpensiveness, and their measurement in physical units ($m.s^{-2}$)(Ibitoye, Hamzaid, Zuniga, Hasnan, et al., 2014; Islam et al., 2013). From this sensors, RMS may be extracted as it correlates with the number of active motor units across time. In the frequency domain, mean power frequency may be computed from the sensor as it is related to motor units firing rate. MMG is also able to detect muscle fatigue (Al-Mulla et al., 2011; Beck et al., 2005; Ibitoye, Hamzaid, Zuniga, and Wahab, 2014; Islam et al., 2013; Orizio, 1993). Despite an increasing interest in MMG last years, only a few studies analyzed MMG signals during functional activities and neither studies were found on using MMG for ergonomic assessment in an occupational environment. We might think that EMG has been used for that purpose, but it has not been the case, mainly for technical reasons (*e.g.* electrical interferences, impedance, skin preparation, sensor placement) (Farina, 2006; Gazzoni, 2010). Given the fact that MMG presents technical advantages over EMG, such as ease of fixation, non-sensitivity to impedance, and less sensitivity to sensor placement (Silva et al., 2005), MMG sensors may thus be employed as a quantification tool for risk assessment exposure in physical ergonomics. This would permit to obtain information about what is occurring "internally" during an occupational task, and hence contributing to fill the gap between biomechanical exposure and pathomechanical process underlying MSDs.

The global objective of this research axis is to develop, validate and apply a methodology based on MMG for ergonomic assessment (see Figure 2.1). To this aim, MMG sensors and processing from Moten company will be used and compared to traditional EMG sensors during isometric and dynamic tasks through a laboratory-based experiment (Correa et al., 2022). On the basis of this validation study, MMG sensors will be employed in the field to analyze occupational tasks and quantify the physical risk of exposure. This research is currently conducted through Matthieu Correa's doctoral project (CIFRE PhD agreement, 2020-2023) in collaboration with Pr Isabelle Siegler (CIAMS) and Maxime Projetti (Moten company).

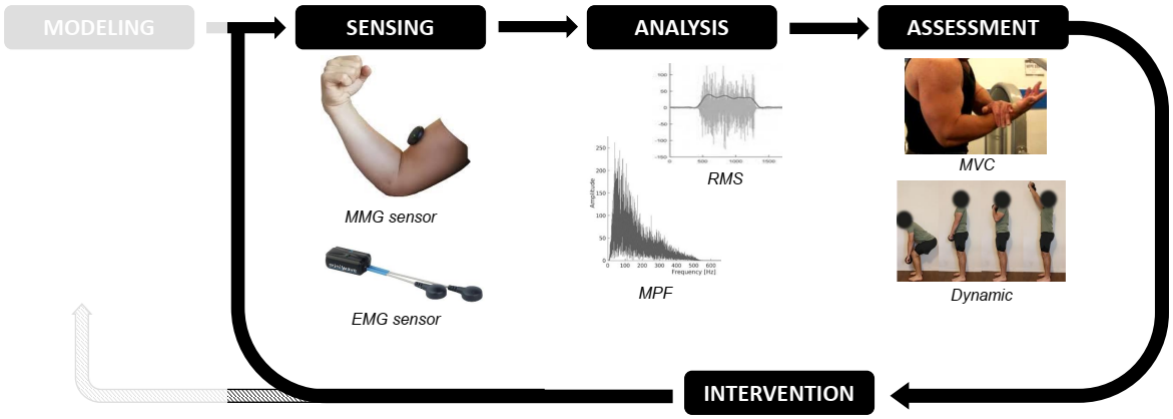


Figure 2.1: Research objectives of the 1st axis into the physical ergonomics framework. MMG sensors will be compared to EMG sensors, and analyzed through time and frequency domains, for isometric (MVC) and dynamic muscle contractions. These results will permit to define a MMG-based methodology for ergonomic assessment.

2.2.2 A methodology based on on-body sensors to prevent sport injuries

Although football is one of the leading sports in the world with over 275 million people regularly playing (FIFA, 2019), it is also a sport with one of the highest injury incidence risks (Bengtsson et al., 2013). In male football, most injuries (59–67%) consist of non-contact injuries, muscular strains being predominant (Ekstrand, Hagglund, et al., 2013). Preventing these injuries appear particularly critical for professional teams with tight competitive timetable associated to financial issues. Non-contact injuries look more frequent in the second half and towards the end of the match, likely due to fatigue accumulation (Verschueren et al., 2020). The number of matches that a player plays in a week may also influence the injury rate (Bengtsson et al., 2013), as well as excessive training load (Gabbett, 2016). Fatigue and excessive training load have thus been identified as major injury risk factors. Despite this finding, injury rates for muscle and severe injuries remained constant during the 2000s, hamstring injuries even increasing during this decade (Ekstrand, Walden, et al., 2016). Better in-field biomechanical measurements seem required to identify critical risk factors, and thus decrease number of non-contact injuries in football.

Ground reaction forces (GRF) have great potential for monitoring players' fatigue and training load, as they accurately provide biomechanical load, impact forces and total impulse data (Vanrenterghem et al., 2017). Although IMUs are currently used to estimate GRF (Buchheit, Gray, et al., 2015), these estimations are not reliable in all conditions on the field (Buchheit and Simpson, 2017; Scott et al., 2016). Moreover, very few of the available parameters characterizing an athletes' training load have shown strong scientific validity (Halson, 2014). Thus it appears necessary to better focus

on GRF to prevent non-contact injuries. Previous studies about GRF estimation for football suffered from methodological drawbacks like human-based mechanical simulations (Galbusera et al., 2013), or standard force platforms limiting the number of steps (Schrier et al., 2014). However, GRF are related to adaptations between the player, his shoes and the surface. Any change from ecological and typical playing conditions may therefore alter the relevance and validity of the investigation. There is thus a lack of adequate devices or methods to measure (or accurately estimate) GRF on a football field in order to enhance injury prevention strategies.

To address this issue, instrumented studs able to record on-field GRF have been recently developed (Phyling company). These studs may record GRF without altering standard playing conditions. Before using this system into an injury prevention strategy in soccer, it is necessary to validate its relevance for biomechanical analysis (see Figure 2.2, top row). To this aim, GRF data provided by the instrumented studs have to be compared with referential data from a force plate through a laboratory-based experiment during running and countermovement jumps. Then, GRF data have to be obtained in ecological conditions for the same movements, and compared with previous studies from the literature. These two investigations have been recently published in *Sensors* journal (Karamanoukian et al., 2022). Fatigue has been showed to be a major risk factor in sport injury appearance. The ability of this innovative system to detect fatigue has therefore been tested in ecological conditions (manuscript writing in progress). Finally, this system will be used as a tool for monitoring training load through a longitudinal study in order to prove its efficiency for injury prevention. This research is currently conducted through Alexandre Karamanoukian's doctoral project (CIFRE PhD agreement, 2020-2023) in collaboration with Romain Labbé and Jean-Philippe Boucher (Phyling company).

This injury prevention framework will be soon developed and applied in cycling (2022-2025), still in collaboration with Phyling company (see Figure 2.2, bottom row). In this sport, 64% of injuries are appearing during training and among them, 90% are considered as MSDs (De Bernardo et al., 2012). Knee joints are particularly at risk during this activity (Clarsen et al., 2010). Thus it may be critical to accurately analyze this motion in order to optimize quantification of training load and thus prevent these cycling-based MSDs. Tridimensional kinematics may be obtained with optoeletrconic systems but they may be hardly used in the field due to their space organization. Embedded sensors therefore appear as a relevant alternative in order to obtain data during training, especially with IMUs (Cordillet et al., 2019). This analysis might be completed by force/torque sensors located in the pedal and power sensors placed into the crankset (Bini and Priego-Quesada, 2022). This would permit to obtain both force exertions and kinematics directly in the field through an embedded methodology. Through Thomas Chevallier's doctoral project (CIFRE PhD agreement, 2022-2025) in collaboration with Laetitia Fradet (PhD advisor, Université de Poitiers), and Romain Labbé and Jean-Philippe Boucher (Phyling company), the aim of this research is to develop biomechanical

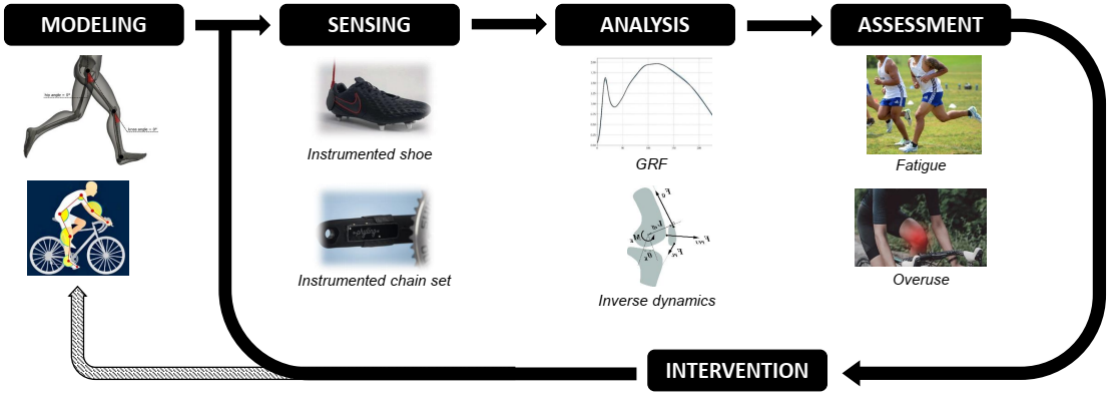


Figure 2.2: Research objectives of the 2nd axis into the physical ergonomics framework. For soccer applications, the instrumented studs will be used to analyze GRF under fatigue conditions. This system will then be used to monitor players' training load through an ergonomic intervention aiming at preventing injury appearance. For cycling applications, the instrumented bike will be coupled to IMUs to deduce biomechanical loads at joint level. This will permit to identify injury risk factor for cycling. This system will be employed through an ergonomic intervention in a professional team and this will permit to update the biomechanical model for in-field applications.

models associated to a reduced set of embedded sensors in order to quantify joint loads in the field in cycling. The first objective will be to validate the methodology through laboratory experiments. Motion data from high-level cyclists will be simultaneously collected in order to identify risk factors that may induce injury (2nd objective). The last objective will be to apply the methodology on few cyclists to establish joint load evolvement through the training season. All these developments will be discussed with high-level cycling teams and the cycling federation.

2.2.3 A decision support tool to evaluate passive exoskeletons

In terms of ergonomic interventions, passive exoskeletons have introduced new means for improving the conditions of workers and for reducing the risk of MSDs. Performance of passive exoskeletons is based on a re-distribution of weight or human movement through springs or dampers (Lee et al., 2012). Their specific configuration is usually depending on the part of the body to which it provides support or help (Iranzo et al., 2020). Regarding the upper body, some disposals are dedicated to the lumbar area in order to help for weight lifting or any other types of manipulation where the lower back is under stress and at risk of injury (Manns et al., 2017; Toxiri et al., 2017; Weston et al., 2018). In addition, there are upper limb exoskeletons with specific structures that can relieve the strain on shoulders, elbows, or wrists. They are typically intended to ease tasks consisting of tool manipulation or overhead works, mainly found in repetitive cycles (Ebrahimi, 2017; Huysamen

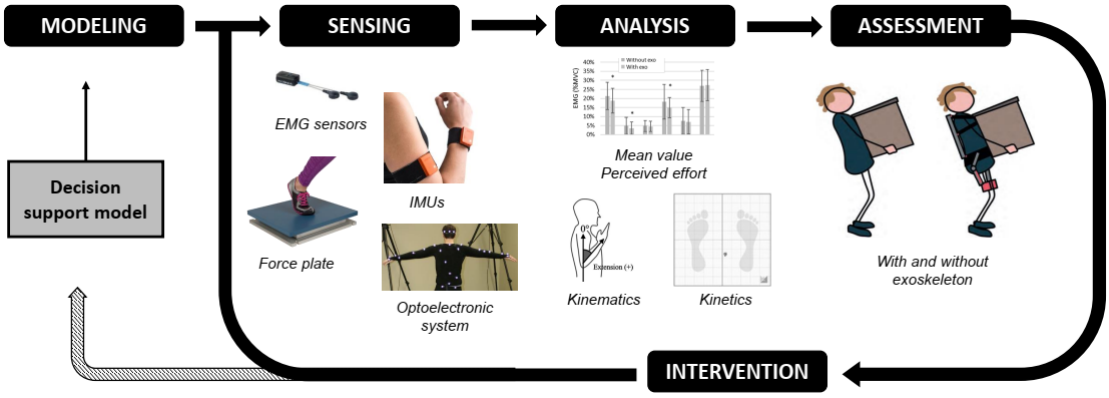


Figure 2.3: Research objectives of the 3rd axis into the physical ergonomics framework. Different kinds of sensors will be used to obtain kinematics, dynamics and internal data into laboratory and in-field experiments. These data will be analyzed to characterize human motor control with and without a passive exoskeleton. This results will be implemented into a database and a machine learning process will be applied. This will permit to support decision when a passive exoskeleton (trunk and upper body) has to be assessed.

et al., 2018; Otten et al., 2018). However, some researchers showed that these assisting tools may also induce discomfort and physical stress (de Looze et al., 2016; Eurofound, 2017).

To assess the benefits of using a passive exoskeleton, their biomechanical impact has been investigated through with-and-without experiments. As previously mentioned, muscle activity is widely employed to characterize the influence of an exoskeleton. Motion kinematics and kinetics may also be used to conduct this analysis (*e.g.* optoelectronic systems, IMUs, force plate) (Ebrahimi, 2017; Maurice et al., 2020). Some other researchers emphasized on the subjective perceptions and considered the degree of acceptance as an important factor for drawing conclusions (Spada et al., 2017) However, there is no hierarchy in the significance of these data according to the occupational task and conditions. Moreover, most of these comparative studies have been carried out in laboratory conditions, and very little is known pertaining to what happens during in-field conditions.

The aim of this research axis is twofold: (i) investigating the influence of passive exoskeletons (trunk and upper limbs) on the operator using subjective methods and embedded sensors, during laboratory and in-field experiments, and (ii) creating and validating a decision support model on the basis of these experimental data (see Figure 2.3). This model will help future users to select embedded sensors and procedures for the purpose of assessing a passive exoskeleton. This research recently started through Kevin Lebel's doctoral project (Plan de Relance PhD agreement, 2022-2025) in collaboration with Bérenger Le Tellier from ErgoSanté Technologie company (Anduze,

France). This project may also benefit from a collaboration with Hôpital La Pitié Salpêtrière (Paris, France). More precisely, after conducting an ergonomic assessment with embedded sensors on care assistants in a surgery unit (Koskas, 2021), an experiment with an upper limb exoskeleton has been performed on the same care assistants during surgery tools cleaning tasks (Arnoux, 2022).

2.2.4 Transparency of an active exoskeleton and ergonomic benefits

Concerning active exoskeletons, we previously showed that: (i) transparency is a critical prerequisite for HEI, and (ii) EMG signal may be used to intuitively control an exoskeleton (1.4). By combining these previous developments, the aim of the current research axis is to improve transparency of an active upper limb exoskeleton by detecting operator's intent. This upstream identification of operator's intent might be performed on the basis of biological signals appearing *before* the visible motor task, like electroencephalographic (EEG) and EMG signals (see Figure 2.4).

Indeed, EMG signals may be used to predict movement as they benefit from an electromechanical delay of 50 to 100 ms before movement start (Begovic et al., 2014). As movements of the upper limb may be resumed to shoulder and elbow torques, the first objective is to related EMG signal to muscle forces in order to estimate joint torques. Although multivariate linear regression models (Ullah and Kim, 2009) and muscle synergy models (Delis, Berret, et al., 2013) have been developed, neuromusculoskeletal models may be of interest as they may consider muscle distortion due to joint angle variation during the movement (Hill, 1938), and they have been showed to predict joint torque accurately (Sartori et al., 2014). However, these models may be time consuming due to calibration process and their real-time performance may be questionable (Lotti et al., 2022). These two scientific issues, *i.e.* calibration and real-time use, will be addressed through specific software tools to reduce computation time. Moreover, EMG signals will be collected through both EMG and high density EMG sensors to better calibrate the model and deduce the best reduced configuration of sensors.

At an earlier stage from movement appearance, *i.e.* motor preparations stage, it appears feasible to decode some user's intentions from non invasive EEG signals through deep learning algorithms (Mammone et al, 2020). These neural signals may even be employed to model decision processes upstream to the motor preparation, thus permitting to identify these processes at task level (Yang et al, 2020, Si et al, 2020). Detecting the user's intent on the basis of EEG signals for controlling an assistive device is considered as a disruptive innovation for future robotic developments (Waldert et al., 2009). Combining this early-stage detection of intent (*e.g.* direction of the movement) based on EEG to an EMG-processing stage (*e.g.* intensity of the movement) may constitute an innovative approach for improving transparency and design of future exoskeletons. In comparison to previous research performed on the ABLE exoskeleton on one DOF, this research will be applied

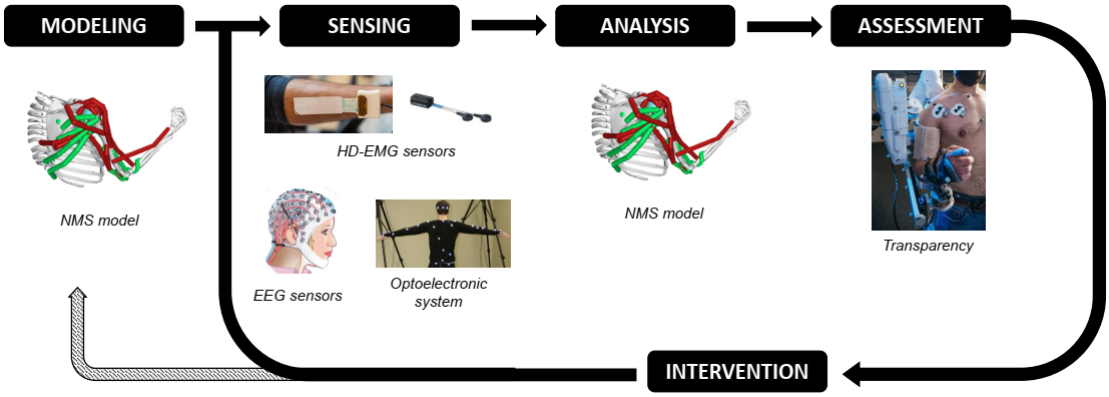


Figure 2.4: Research objectives of the 4th axis into the physical ergonomics framework. In addition to kinematics, EEG and high density (HD) EMG sensors will be used to feed a neuromusculoskeletal (NMS) model of the upper limb. This model will permit to relate muscle activity to joint torques. Real-time integration of these commands (reduced-to-complete muscle models) will be assessed through the measurement of transparency into HEI. These data will be also used to improve the corresponding neuromusculoskeletal model (*e.g.* calibration process).

on movements with four DOF, *i.e.* shoulder and elbow movements. The impact of this bioinspired control law will be tested on several human participants, taking account of new metrics previously described (see section 1.4.1.2). These developments will be performed through Lucas Quesada's doctoral project (CDSN PhD agreement, 2021-2024) in collaboration with Pr Michel-Ange Amorim (CIAMS) and Pr Olivier Bruneau (LURPA laboratory, ENS Paris-Saclay).

From a physical ergonomic perspective, all these developments conducted on active exoskeletons may now be applied to prevent MSDs. More precisely, even if transparency of the exoskeleton will continue to be improved, it is possible to simultaneously investigate how an active exoskeleton may guide the user to ergonomic motion space. An ergonomic trajectory may be defined on the basis of observational methods (*e.g.* RULA, REBA, OCRA) and embedded sensors used into the CIAMS platform for HEI are providing these necessary kinematical data in real-time. Although this approach has been developed for human-robot collaboration (Figueredo et al., 2020), it would appear relevant to integrate this objective, *i.e.* following an ergonomic trajectory, into the control law of an active exoskeleton. The research hypothesis is that an exoskeleton is able to guide human motion in an ergonomic manner, even if the subsequent movements do not appear intuitive for the user. The first aim of this research will be to show that specific force fields applied through the exoskeleton permit to guide the human motion to a specific target. The next aim will be to use this technical framework with adapted force fields to design optimal trajectories from an ergonomic perspective, thus showing that an active exoskeleton may be used to find the best compromise

between motion efficiency and prevention of MSDs. This path of research will be developed through Waldez Gomes' postdoctoral fellowship (EXOMAN ANR project) in collaboration with Pr Bastien Berret (CIAMS).

2.2.5 Complementary research projects

Although it is not directly related to the current research framework, I had the opportunity to develop collaborations with companies and institutions through my role of supervisor into the Master STAPS : IEAP. That is how things began with SAMMed company, led by Thomas Poirier, that develops human gait analysis system, mainly based on pressure sensor mat (Zeno, Protokinetics, USA). As these systems are dedicated to clinical applications, it has to be adjusted to populations with motor deficiencies. Gait analysis may thus be conducted on people with CP with pressure sensor mat. However, this population do not have typical gait patterns and their footprints may be misinterpreted by the system, leading to abnormal values in the gait analysis report. To take into account these particular biomechanical patterns, it is necessary to design specific algorithms with adjusted boundary conditions. Through Master STAPS : IEAP internships (Souphiane Jender in 2018-2019, Clémentine Pignat in 2019-2020, Arthur Fabre in 2020-2021, Fabien Wack in 2021-2022), this applied research question has been investigated on the basis of experimental procedures (*e.g.* comparison with optoelectronic systems, use of IMUs to complement gait analysis, Research protocol CER-Paris-Saclay-2021-299). To go further, a clinical measurement method for postural control (during static and gait conditions) based on the analysis of plantar supports and centre of gravity, is currently under development. This project will be based on Fabien Wack's doctoral project (CIFRE PhD under process, 2022-2025) in collaboration with Arnaud Gouëlle (PhD advisor, Université de Reims), and Thomas Poirier (SAMMed company).

In the same way, some collaborations have been developed with Centre for Nanoscience and Nanotechnology (Université Paris-Saclay). More precisely, the Department of Microsystems and Nanobiofluidics (represented by Emile Martincic and Pierre-Yves Joubert) are developing innovative capacitive pressure sensors that can be used for movement analysis. After suggesting an integration of this type of sensors into the saddle for biomechanical analysis in horseriding (see section 1.5), a system for the analysis of biomechanical constraints between a stump and a socket of a lower limb prosthesis has been investigated (case study with a lower-limb amputee). This work has been initiated by Alexandre Lelièvre during his Master 1 internship (2020-2021) in collaboration with an orthoprosthesist (Pommier Orthopédie, Les Ulis, France). This project was continued in 2021-2022 with Juliette Souchu who performed her Master 1 internship into the Centre for Nanoscience and Nanotechnology under the supervision of Emile Martincic and Pierre-Yves Joubert.

Finally, in the frame of Olympic Games 2024 in Paris, an interdisciplinary research project is currently under development with my colleagues from the CIAMS laboratory, Caroline Teulier (Motor control) and Christopher Hautbois (Sport management), to analyze the influence of an international sport event on the practice of sport for people living around. This analysis will be based on interviews, questionnaires and embedded sensors (*e.g.* activity trackers) worn by participants during this longitudinal study (12 and 6 months before the event, during the event, 6 months after the event). The analysis will focused particularly on young and elderly people for public health reasons. This project will be conducted in collaboration with the city of Bures-sur-Yvette (agreement given) and other cities from the Orsay geographical area.

Chapter 3
3 Curriculum vitae

THIS chapter gives a summary of my educational and academic activities in link with my research. As quickly explained, I did a PhD in Sport Biomechanics at Université Rennes 2 (Rennes, France) about the development of VR-based methodology for the analysis of visual information uptake in handball goalkeeping. Five peer-review articles have emerged from this PhD thesis (Journal of Sports Science & Medicine, Presence: Teleoperators and Virtual Environements (x2), IEEE Computer Graphics and Applications, Human Movement Science). Between 2010 and 2012, I was a postdoctoral researcher at Centre National de la Recherche Scientifique into the Biomechanics and Bioengineering laboratory (Université de Technologie de Compiègne, France) working on the COGNITO European project. A salient feature of this postdoc is the publication of an article in Applied Ergonomics with more than 300 citations in nine years (Vignais, Miezal, et al., 2013). From 2012 to 2014, I was a postdoctoral fellow at McMaster University (Hamilton, Ontario, Canada) working on ergonomic assessment based on on-body sensors. In addition to the three peer-review publications associated to this fellowship (International Journal of Human Factors Modelling and Simulation, Critical Reviews in Biomedical Engineering, Applied Ergonomics), this gave me the opportunity to develop international collaborations and meet outstanding future colleagues. In 2014-2015, I spent one year into the ERCOS team (Université de Technologie de Belfort-Montbéliard, Montbéliard, France) as an Assistant Professor. The very large number of collaborations with the industrial sector provided an excellent basis for continuing the development of physical ergonomic assessment methodology based on on-body sensors. Since September 2015, I am Maître de Conférences (Associate Professor) at the Université Paris-Saclay (Orsay, France) where I develop my multidisciplinary work with motor control specialists, ergonomists, roboticists, and engineers from the private sector. In 2015, I was awarded with the PEDR (national PhD supervision & research bonus).

3.1 General information

VIGNAIS Nicolas

Date of birth: February 21, 1982

Family situation: separated (2 children in shared custody)

Professional situation: Maître de Conférences, Faculté des Sciences du Sport, Université Paris-Saclay, "Complexité, Innovation, Activités Motrices et Sportives" (CIAMS) laboratory (EA4532)

Nationality: French

Address: Université Paris-Saclay, Bâtiment 335, Bureau 30.1, 91405 Orsay cedex

Telephone: +33 1 69 15 47 03 (office)

Email: `nicolas.vignais@universite-paris-saclay.fr`

Home Page: https://sites.google.com/site/nicolasvignaishomepage/

3.2 Scientific education

From Sept. 2010 to Aug. 2012 Postdoctoral researcher at the Centre National de la Recherche Scientifique into the Biomechanics and Bioengineering laboratory (UMR CNRS 7338, Université de Technologie de Compiègne, France), under the supervision of Prof. F. Marin, collaborations with Dr. M. Miezal and Dr. G. Bleser (DFKI, Kaiserslautern, Germany).

From Dec. 2005 to Dec. 2009 PhD in Sport Biomechanics at Movement, Sport and health Sciences laboratory (M2S) (Rennes 2 University, Rennes, France), entitled: "Introduction and evaluation of a methodology based on virtual reality for visual information uptake analysis of handball goalkeeper" (graduated with honours). Advisors: Pr. P. Delamarche (Physiologist and Biomechanist), Dr. R. Kulpa (Biomechanist and Computer scientist) and Dr. B. Bideau (Biomechanicist). **Jury** (defense on Dec. 3rd 2009):

Mme Cathy Craig	Professeur, Queen's University of Belfast, Ireland	Examinatrice
M. Stéphane Vieilledent	MCF-HDR, Université de Bretagne Occidentale, Brest	Rapporteur
M. Daniel Mestre	Professeur, Institut des Sciences du Mouvement, Marseille	Rapporteur
M. Stéphane Donikian	Professeur, Université de Rennes 1	Examinateur
M. Paul Delamarche	Professeur, Université de Rennes 2	Directeur de thèse
M. Benoit Bideau	MCF, Université de Rennes 2	Directeur de thèse

From 2003 to 2005 Master of Science in Cellular and Integrative Physiology for Physical Activities, Human Movement Modeling, at Rennes 2 Université (mention Bien).

From 2000 to 2003 Bachelor of Science in Sciences and Techniques of Physical Activities and Sport (Licence Entrainement Sportif), at Rennes 2 Université (mention Assez Bien).

3.3 Career

Curriculum

From 2020 to 2024 "Prime d'encadrement doctoral et de recherche" (PEDR) (national doctoral supervision and research award) from Université Paris-Saclay (top 50% of applicants).

Since Sept. 2012 Associate Professor ("ăMaître de Conférencesă") in CIAMS laboratory, Faculté des Sciences du Sport, Université Paris-Saclay, Orsay, France.

2010 Qualification in CNU 74 (STAPS)

2012 Qualification in CNU 60 (Mechanics)

2013 Qualification in CNU 16 (Ergonomics)

Highlights

- Highly cited paper Award in 2016: My article published in 2013 (Vignais, Miezal, et al., 2013) was one of the five most highly cited papers published in Applied Ergonomics during 2014, 2015 and up until June 2016. Until today (26/08/22), this article gained 305 citations.

Metrics (as of August 2022) h-index (according to Google Scholar): 14

Number of citations (according to Google Scholar): 1195

3.4 Supervision work

PhD Student supervision

Alexander MacIntosh	
Date:	Sept. 2016 – Dec. 2019 (completed)
Location:	Université Paris-Saclay and University of Toronto (cotutelle)
Title:	" Biofeedback-Enhanced Interactive Computer Play to Improve Hand Function in Youth with Cerebral Palsy "
Role:	Co-supervisor (30%) with Dr. Vincent Vigneron (30%) and Dr. Elaine Biddiss (40%)
Last known position:	Research Manager and Scientist at Altus Assessments (Toronto, ON, Canada)
Related Publications:	6 International conferences, 5 publications from PhD work (PloS One, Syst. Rev., Disab. & Rehab., IEEE Trans. Neur. Syst. Rehab. Eng., Assist. Technol.)
Awards	• International: Excellence Eiffel Fellow (Campus France, d'15 000), Student Abstract Award (European Society of Biomechanics, 355d') • National: Travel Scholarship (Kids Brain Health Network, $500), Travel scolarship (Société de Biomécanique, 400d'), Globalink Research Award (Mitacs, $6 000), Michael Smith Foreign Study Supplement (CIHR, $6 000), Doctoral Research Award (CIHR, $105 000 / 3 years), Award of Fédération Demeny-Vaucanson 2017 (500d')

Simon Bastide	
Date:	from Sept. 2017 to June 2021 (completed)
Location:	Université Paris-Saclay: CIAMS and CEA-LIST
Title:	" Adaptation of Humans to the interaction with an upper-limb exoskeleton: analysis and modeling of control laws "
Role:	Co-supervisor (30%) with Prof. Bastien Berret (50%) and Dr. Franck Geffard (20%)
Last known position:	Data Scientist at AKKA Technologies (Toulouse, France)
Related Publications:	5 international conferences (SB 2017 and 2019, IROS 2018, ICRA 2020, PMC XII) and 1 publication from PhD work (Frontiers in Bioengineering and Biotechnology) – 1 article in preparation
Awards	Award of Fédération Demeny-Vaucanson 2018 (500d')

Benjamin Treussart	
Date:	from Sept. 2017 to March 2021 (completed)
Location:	Université Paris-Saclay: CIAMS and CEA-LIST
Title:	" Design and study of a system to control intuitively an exoskeleton in order to assist load carrying "
Role:	Co-supervisor (40%) with Prof. Frédéric Marin (20%) and Dr. Franck Geffard (40%)
Last known position:	Research engineer at CEA Tech (Nantes, France)
Related Publications:	2 international conferences (IEEE MoRSE 2019, ICRA 2020) – 1 article in preparation
Awards	Award of Fédération Demeny-Vaucanson 2018 (500d')

Alexandre Karamanoukian	
Date:	Started in Sept. 2020
Location:	Université Paris-Saclay and Phyling company (CIFRE agreement)
Title:	" Development of a football-specific injury prevention tool using studs instrumented with force sensors "
Role:	Co-Supervisor (50%) with Dr. Jean-Philippe Boucher (50%)
Related Publications:	3 international conferences (Sport Physics 2021, SB2021, ACAPS 2021) and 1 publication from PhD work (Sensors) – 1 article in preparation

Matthieu Correa	
Date:	Started in Sept. 2020
Location:	Université Paris-Saclay and Moten company (CIFRE agreement)
Title:	" Development of a mecanomyographic analysis tool for the detection of muscular fatigue and prevention of MSDs "
Role:	Co-Supervisor (30%) with Prof. Isabelle Siegler (CIAMS, 20%) and Dr. Maxime Projetti (Moten, 50%)
Related Publications:	1 international conference (SB2022) – 1 article in preparation

Lucas Quesada	
Date:	Started in Oct. 2021
Location:	CIAMS and LURPA (CDSN PhD agreement)
Title:	" Optimizing the transparency of an exoskeleton for load carrying via operator intention detection "
Role:	Co-Supervisor (30%) with Prof. Michel-Ange Amorim (40%) and Prof. Olivier Bruneau (30%)

Kevin Lebel	
Date:	Started in Jan. 2022
Location:	Université Paris-Saclay and Ergosanté Technologie company (Plan de Relance PhD agreement)
Title:	" Development of an evaluation methodology for Physical Assistance Devices related to professional tasks "
Role:	Co-Supervisor (50%) with Prof. Isabelle Siegler (25%) and Dr. Bérenger Le Tellier (Ergosanté, 25%)

Thomas Chevallier	
Date:	Started in Oct. 2022
Location:	Université Paris-Saclay and Phyling company (CIFRE agreement)
Title:	" A methodology for biomechanical analysis of high-level athletes based on on-body sensors: applications to cycling "
Role:	Co-Supervisor (25%) with Dr. Laetitia Fradet (25%) and Dr. Jean-Philippe Boucher (Phyling, 50%)

Finally, I am involved as a collaborator/co-supervisor in two PhD theses of previous Master students (see above, A. Karamanoukian, T. Chevallier).

Master student (2nd year) – duration of internship ~4-6 months

Simon Bastide	
Date:	from Feb. 2017 to June 2017
Location:	Université Paris-Saclay, CIAMS and CEA-LIST
Title:	“Impact of wearing an exoskeleton on upper-limb human motricity”
Role:	Co-Supervisor 50% (with Dr. Bastien Berret and Dr. Franck Geffard)
Last known position:	Data Scientist at AKKA Technologies (Toulouse, France) after a PhD with me (30%), Bastien Berret (50%) and Franck Geffard (20%)
Related publication	1 paper in Computer Methods in Biomechanics and Biomedical Engineering (2017)

Flavien Mazzon	
Date:	from Feb. 2017 to June 2017
Location:	Physio-Massage Training Institute (Saint-Michel) and Université Paris-Saclay
Title:	“Analysis of functional calibration methods for lower limb joint centres computation "
Role:	Co-supervisor (50%) with T. Poirier (50%)
Last known position:	Wingsuit Instructor and Coach (Inclined Labs AB, Stockholm, Sweden)

Hela Slim	
Date:	from Feb. 2017 to June 2017
Location:	Physio-Massage Training Institute (Saint-Michel) and Université Paris-Saclay
Title:	" Study of the reproductibility of joint centres positions computed by the SCoRE funcitonal method based on different calibration movements "
Role:	Co-supervisor (50%) with T. Poirier (50%)
Last known position:	Health Business Manager at Tessi company (Paris, France)

Ambre Rosse	
Date:	from Feb. 2018 to June 2018
Location:	SAMMed (Villebon, France) and Université Paris-Saclay
Title:	" Development and validation of an algorithm for measuring step orientation based on pressure sensor mat and comparison with an optoelectronic system "
Role:	Co-supervisor (50%) with T. Poirier (50%)
Last known position:	Physiotherapist (Paris, France)

Gabriel Varraut	
Date:	from Feb. 2018 to June 2018
Location:	Décathlon (Thiais, France) and Université Paris-Saclay
Title:	" Ergonomic assessment based on on-body sensors for the redesign of a goods reception area "
Role:	Supervisor
Last known position:	Robotic Storage Platform Area Manager (Amazon, France)

Nima Caën	
Date:	from Feb. 2018 to June 2018
Location:	Voltaire Design (Biarritz, France) and Université Paris-Saclay
Title:	" Preventing musculoskeletal disorders through on-body sensors in saddle manufacturing "
Role:	Co-Supervisor (50%) with Dr Agnès Olivier (50%)
Last known position:	Yoga teacher
Related publication	1 conference in ErgoIA 2018

Dorian Verdel	
Date:	from Feb. 2019 to June 2019
Location:	LURPA (ENS Paris-Saclay) and CIAMS (Université Paris-Saclay)
Title:	" Modeling, identification and control of a 4 DOF active exoskeleton "
Role:	Co-Supervisor (30%) with Dr Bastien Berret (30%) and Prof. Olivier Bruneau (40%)
Last known position:	PhD student with Prof. Bastien Berret and Prof. Olivier Bruneau, and I collaborate with
Related publication	1 International Conference ICRA (2020) and 1 paper in Robotica (2021)

Souphiane Jender	
Date:	from Feb. 2019 to June 2019
Location:	SAMMed (Villebon, France) and Université Paris-Saclay
Title:	" Footprint identification with partial support on pressure sensor mat for gait analysis of people with cerebral palsy "
Role:	Co-supervisor (50%) with T. Poirier (50%)
Last known position:	Pedagogical engineer at Université Paris-Saclay

Tanguy de Vermont	
Date:	from Feb. 2020 to June 2020
Location:	Azergo (Villebon, France) and Université Paris-Saclay
Title:	" Ergonomic assessment of office seats: influence of mechanical parameters
Role:	Supervisor
Last known position:	Workstation layout ergonomic advisor (Azergo, France)

Rémy Caron	
Date:	from Feb. 2020 to June 2020
Location:	CEA-LIST and CIAMS
Title:	" Influence of motor control parameters on the control law of an active upper-limb exoskeleton "
Role:	Co-Supervisor (50%) with Franck Geffard (50%)
Last known position:	Workstation layout ergonomic advisor (Azergo, France)
Related publication	1 preprint paper in bioRxiv (2021)

Maxime Ruaux	
Date:	from Feb. 2020 to June 2020
Location:	CIAMS
Title:	" Ergonomic assessment with on-body sensors: a feasibility study in hospital environment "
Role:	Supervisor
Last known position:	Production manager (ABILIS, France)

Zakaria Jelti	
Date:	from Feb. 2020 to June 2020
Location:	Ergosanté Technologie and Université Paris-Saclay
Title:	" Impact of a passive exoskeleton on user's postures and movements "
Role:	Co-Supervisor (40%) with Simon Bastide (30%) and K. Lebel (30%)
Last known position:	Data Scientist (freelance)
Related publication	1 preprint paper in bioRxiv (2021) and 1 conference ErgoIA 21

Alexandre Karamanoukian	
Date:	from Feb. 2020 to June 2020
Location:	Phyling and Université Paris-Saclay
Title:	" Validation of instrumented studs for fatigue identification in soccer
Role:	Co-Supervisor (50%) with Romain Labbé (50%)
Last known position:	PhD student in CIFRE with me (50%) and J.-P. Boucher (Phyling, 50%)
Related publication	2 conferences (ACAPS 2021 and French Society of Biomechanics 2021)

Ruth Maria Bonet Funes	
Date:	from Feb. 2020 to June 2020
Location:	Holodia and Université Paris-Saclay
Title:	" Virtual reality fitness: determination of user profile based on gender and age "
Role:	Co-Supervisor (70%) with Carole Castanier (CIAMS, 30%)
Last known position:	Data scientist of healthcare solutions

Daniel Koskas	
Date:	from Feb. 2021 to June 2021
Location:	Université Paris-Saclay in collaboration with Hôpital La Pitié-Salpêtrière
Title:	" Physical ergonomic analysis with embedded sensors to prevent musculoskeletal disorders among hospital staff "
Role:	Supervisor
Last known position:	PhD student applicant for a CIFRE agreement
Related publication	1 paper submitted in Applied Ergonomics

Arthur Fabre	
Date:	from Feb. 2021 to June 2021
Location:	SAMMed and Université Paris-Saclay
Title:	" Biomechanical analysis based on a pressure sensor mat and inertial measurement units for spatiotemporal gait analysis "
Role:	Co-Supervisor (50%) with Thomas Poirier
Last known position:	PhD student applicant in Canada

Soyoung Cho	
Date:	from Feb. 2021 to June 2021
Location:	LISV and CIAMS
Title:	" Impact of ESTA upper-limb exoskeleton on human motor control "
Role:	Co-Supervisor (50%) with Abderraouf Benali (50%)
Last known position:	Engineer applicant in South Corea

Thomas Chevallier	
Date:	from Feb. 2021 to June 2021
Location:	Phyling and Université Paris-Saclay
Title:	" Table tennis movement analysis based on inertial measurement units "
Role:	Co-Supervisor (50%) with Romain Labbé (Phyling, 50%)
Last known position:	PhD student with CIFRE agreement with me (30%), Dr. Laetitia Fradet (Université de Poitiers, 30%) and J.-P. Boucher (40%)

Guillaume Sahm	
Date:	from Feb. 2021 to June 2021
Location:	Université Paris-Saclay
Title:	" Ergonomic analysis of human-exoskeleton interactions "
Role:	Co-Supervisor (50%) with Dorian Verdel (50%)
Last known position:	Air force officer cadet

Master student (1st year) – duration of internship ~8 weeks Since my PhD, I supervise 1st year Master students on a regular basis to initiate them to research. Since I am in Université Paris-Saclay, I am usually supervising five to six students every year. When properly conducted, these works were published in International Conferences proceedings (Besombes et al., 2019; Delpierre et al., 2021; Keir, Inman, et al., 2013; Triolet et al., 2019; Vignais, Badier, et al., 2010; Vignais, Greco, et al., 2017).

3.5 Teaching, pedagogic and administrative duties

Since I am “Maître de Conférences” at Université Paris-Saclay, I have been involved in the following teaching activities:

Topic	Degree	Nature	Annual hours (~TD)
“Anatomie”	L1	CM	216h
“Anatomie”	L1	TD	81h
“Pré-requis scientifiques”	L1	TD	10h
“Anatomie”	L2	CM	25.5h
“Anatomie”	L2	TD	13.5h
“Biomécanique”	L2	TD	27h
“Biomécanique APAS”	L2 APAS	CM	12h
“Biomécanique APAS”	L2 APAS	TP	18h
“Déterminants Biomécaniques de la performance”	L3 ES	CM	30h
“Déterminants Biomécaniques de la performance”	L3 ES	TD	74h
“Recherche intégrée”	L3 ES	TD	4h
“Measurement tools for motion analysis”	M1 STAPS : IEAP	CM	38h
“Measurement tools for motion analysis”	M1 STAPS : IEAP	TD	116h
“Measurement tools for motion analysis”	M1 STAPS : IEAP	TP	27h
“Assessment in Physical ergonomics”	M1 STAPS : IEAP	TD	7h
“Understanding Scientific Research”	M1 STAPS : IEAP	TD	10h
“Traitement du Signal - Matlab”	M2 ISMH	TD	168h

Legend: CM = lecture, TD = tutorial classes, IEAP=”Ingénierie et Ergonomie de l’Activité Physique”, ISMH=”Ingénierie et Sciences du Mouvement Humain”

Total service per year

2015-2016: 206h ~TD

2016-2017: 150h ~TD (“décharge néo-MCF” from Univ. Paris-Saclay)

2017-2018: 244h ~TD

2018-2019: 262h ~TD

2019-2020: 165h ~TD (“décharge néo-MCF” from Univ. Paris-Saclay)

2020-2021: 268h ~TD

2021-2022: 250h ~TD

N.B.ă: within Faculté des Sciences du Sport at Université Paris-Saclay, pedagogic duties can be equivalent to a fixed amount of practical tutorials hours (~TD hours) (*e.g.* 30h/year are counted for the Master program responsibility)

Pedagogic duties

- In charge of a pedagogical project – AAP Pédagogie UPSud 2016 – budget 30 kd' (2016-2017)

  Innovative pedagogical materials for human motion analysis: practicals based on wireless electrogoniometers and EMG sensors.

- In charge of a pedagogical project – AAP Pédagogie UPSud 2017 – budget 10 kd' (2017-2018)

  Human body in all dimensions: interactive tablets and "Complete Anatomy" licences for human body display through AR.

- In charge of the University Degree "Sport and Osteopathy" co-organized with Osteopathic Superior School (Champs sur Marne, France) (2017)

  My role was to supervise and coordinate teachnig units agiven at Faculté des Sciences du Sport at Université Paris-Saclay (~10 students).

- In charge of Anatomy discipline at Bachelor level (from 2018).

  My role is to supervise and coordinate the teaching of Anatomy at Faculté des Sciences du Sport at Université Paris-Saclay (~750 undergraduates involved and internal/external teachers).

- In charge of a pedagogical project – AAP Pédagogie Paris-Saclay 2019 – budget 40 kd' (2019-2020)

  Innovative practicals based on IMUs (XSens Awinda system).

- In charge of a pedagogical project – AAP Pédagogie Paris-Saclay 2021 – budget 29 kd' (2021-2022)

  AMaCaP project: Gait analysis based on pressure sensor mat (Zeno system, Protokinetics) for practicals.

- In charge of Master program (M1 "ăSTAPS : IEAP " - ISMH path) for 3 years (2017-2020)

  With the newly created Université Paris-Saclay, new Masters were developed and ported by several Universities and Engineer Schools to reinforce collaborations and reduce costs.

  The Master Program STAPS : IEAP is part of the “Sport, Movement, Human Factors” Graduate School (https://www.universite-paris-saclay.fr/graduate-schools/graduate-school-sport-mouvement-facteurs-humains).

  My role was to recruit the teachers, select the students/candidates, organize the exams, create the schedule, supervise internships, organize oral examinations, maintain the website of the formation (https://www.universite-paris-saclay.fr/formation/master/staps-ingenierie-et-ergonomie-de-lactivite-physique), invite professional speakers and interaction with companies and sport federations, and manage any other issues related to the Master program (~20 graduate students).

- In charge of the full Master program STAPS : IEAP and the 2nd year (ISMH path) (since 2020)

  My supplemental role (see above) is to organize diploma, carefully supervise internships (paid internship from 4 to 6 months), and represent the Master program into the Graduate School.

Administrative duties

- Innovation Referent at Faculté des Sciences du Sport (2017-2019): information dissemination about entrepreneurial projects into Université Paris-Sud, in collaboration with Prof. Pascal Corbel (Vice-president on Enterprise Relationships and Continuing Education) and Nicolas Lecompte (in charge of Entrepreneuriat Division at Université Paris-Sud).
- Enterprise Relationships referent for Master program STAPS : IEAP (since 2019): identification of enterprises from the sector, contacts, meetings, collaboration agreement setup, companies referencing.
- Scientific leader of the MaturActions project entitled " Continuous ergonomic analysis based on embedded sensors " which aims to emphasize research work from a laboratory (2018-2019). This work was performed by 15 students coming from different sectors (Mathematics, STAPS, Public Health, Physics, Law). Administrative coordination was conducted by Nicolas Lecompte (in charge of Entrepreneuriat Division at Université Paris-Sud).
- Scientific leader of an educational project conducted by school students (Charles Peguy high school, Palaiseau) and coordinated by François Tixier (Technology professor) (2018-2019).

"C-Génial 2019" competition winner (Scientific Mediation award) and "Faites de la Science 2019" award (5th Price of the Paris-Saclay Community).

- Academic councillor into the Commission of Learning and Students Life (CFVU) at Université Paris-Saclay (2020-2024) (elected on Ensemble voter list driven by S. Retailleau, former University president). Through this role, I contribute to the development and definition of learning strategies into University. I also participate to the commission of careers of teachers and researchers.
- Task officer for the Conférence des Directeurs et Doyens (C3D) STAPS on the Master STAPS : IEAP (from 2022). The objective is to improve the exposure of this Master program for students in ccordination with Master of Ergonomics and Human Factors.

3.6 Scientific activity

Invited talks

- "Biomechanics applied to ergonomics: materials, methods and modeling". Research symposium of 'Ecole Supérieure d'Ostéopathie'. Champs sur Marne (France), November, 2016.
- "Workstation analysis and new technologies". Workshop 'Innovation, Sport, Entreprise'. Université Paris-Descartes (France), 25 of May, 2018.
- "Physical risk factors identification based on body sensor network combined to videotaping". 30th French Society for Hospital Hygiene Annual Congress. Strasbourg, 5-7 of June, 2019.
- "Assessing physical ergonomics with on-body sensors and using real-time biofeedback to prevent musculoskeletal disorders". Scientific seminar at the Kite Research Institute, University Health Network. Toronto, 10 of December, 2019.
- "A motor control approach to Human/Exoskeleton Interaction". Scientific seminar at the McMaster Occupational Biomechanics Laboratory, Department of Kinesiology, McMaster University. Hamilton, 11 of December, 2019.
- "Preventing musculoskeletal disorders with on-body sensors and real-time biofeedback". National Tsing Hua University & Université Paris-Saclay Bilateral Virtual Symposium: Biomedical Smart Devices and Characterization Tools. November 18 – 20, 2020.
- "Preventing Injuries through Embedded sensors - Application in Soccer". 1st International Conference of Indian Society of Sports and Exercise Medicine, ISSEMCON 2022. March 24 – 26, 2022.

Scientific collaborations (currently active)

National

- ENS Paris-Saclay (Prof. O. Bruneau). Topic: identification methodology for an upper-limb exoskeleton, bio-inspired command laws.
- CEA-LIST (Dr F. Geffard). Topic: Human-Exoskeleton Interaction analysis, motion analysis for cobotics.
- Université de Poitiers (Dr L. Fradet). Topic: Biomechanical modeling for high-level sport analysis, application to cycling.
- Université de Reims Champagne-Ardenne (Dr A. Gouelle). Topic: human gait analysis from pressure sensors mat and inertial systems.

International

- University of Kaiserslautern, WearHealth group (Dr G. Bleser et Dr. M. Miezal, Germany). Topic: development and validation of biofeedback for motion optimization, applications to gait analysis and physical assistance.
- CleanHospitals European Association (Pr D. Pittet, Suisse).Topic: physical ergonomic assessment and assistance through embedded sensors into an hospital environment.

Scientific mediation

Participation to several projects towards scientific communication to general public, including:

- Explore les Sciences du Sport (with Dr C. Teulier and Dr O. Labaune): animation of scientific workshops into primary schools from the close area. This project received a specific budget from Diagonale Paris-Saclay to buy low cost materials dedicated to motion analysis (force plate, grip sensors, light cells, etc.) (budget: 5 kd').
- Jeudi de la recherche (alone): presentation of research topics to a wide public.
- Fête de la Science (CIAMS laboratory): reception of school public and animation of workshops for a wide public.

Research grants

2011 Co-PI of a Work Package from an ANR project untitled MANDARIN (2011-2015) (with Prof. F. Marin): "Haptic manipulation for industrial operations in virtual environments" (budget: 150 kd'). I contributed to the writing of this work package.

2014 PI of a scolarship from the Centre of Research Expertise for the Prevention of Musculoskeletal Disorders (CRE-MSD): “Developing a real-time biomechanical feedback system for reactive and proactive ergonomics applications” (budget: 9.8 kd’). This work resulted in the publication Rizzuto et al. (2019).

2017 Co-PI of a Shared Research Equipment project (with Prof. B. Berret): " Platform for the analysis and modeling of Human/Exoskeleton interactions” (budget: 55 kd’). In collaboration with CEA-LIST and LURPA (ENS Paris-Saclay) laboratories.

2019 Laureate of the MERR scolarship (Mobilité pour l’Elaboration de Réseaux de Recherche) (budget: 1.2 kd’): Development of a research network in Ontario, Canada (University of Toronto, McMaster University).

2019 Co-PI of a Work Package from an ANR High Level Sport Performance project untitled OPTICC 2024 (coordinated by Prof. F. Cottin et Dr. A. Olivier) (budget: 2 360 kd’): “Optimization of horse/rider interactions for performance during Eventing”. In collaboration with C2N (Université Paris-Saclay), PPrime (Université de Poitiers), ’Marqueurs prognostiques et facteurs de régulation des pathologies cardiaques et vasculaires’ (Université de Franche-Comté) laboratories, and CNRS, INRA, and CREPS of Poitiers, IFCE, Hippolia, Equi-Test, Movin’Smart, CGMV Production. This project was retained in the last 10 finalist projects but it has not been finally funded.

2020 Co-PI of a Shared Research Equipment project (with Dr. A. Olivier): " Platform for the analysis of riding/horse interactions " into the CIAMS laboratory (budget: 20 kd’).

2020 PI of a Work Package from an ANR project untitled EXOMAN (2020-2023) (coordinated by Prof. B. Berret) (budget: 560 kd’): " Measuring human movement in Human/Exoskeleton Interactions ". In collaboration between CIAMS (Université Paris-Saclay), ISIR (Sorbonne Université), LIST (CEA), LURPA (ENS Paris-Saclay) and CeRSM (Université Paris Nanterre) laboratories.

2020 Co-PI of a iCODE (Institute for Control and Decision) (IDEX ParisSaclay) “non-thematic” project (budget: 10.7 kd’) (with Prof. B. Berret): “Control of an Upper Limb Exoskeleton through Dynamical Data (CULEDD)”.

2020-2024 Research and Doctoral Supervising Award (PEDR)

2022 Co-PI of a H-CODE (Human in the loop for Control and Decision Institute) (IDEX ParisSaclay) “non-thematic” project (budget: 9.8 kd’) (with PhD student L. Quesada): “Using high density electromyography for the evaluation and calibration of neuromuscular models for the study of human movement and its assistance”.

Scientific Referee

- Experimental Brain Research, Ergonomics, PloS One, Applied Ergonomics, Human Factors, Human Movement Science, Journal of Biomechanics, Movement and Sport Sciences, New Media & Society, Presence: Teleoperators and Virtual Environments, Multibody System Dynamics, Computers & Industrial Engineering, Computer Animation & Virtual Worlds, ICRA, IROS, International Journal of Environmental Research and Public Health.
- Review Editor for Applied Ergonomics journal
- Topical Advisory Panel Member of International Journal of Environmental Research and Public Health journal
- Referee for CIFRE ANRT scolarships (x2), Natural Sciences and Engineering Research Council of Canada (NSERC)

Thesis expertise

- Reviewer for P. Plantard PhD defense: " Objectivation et standardisation des évaluations ergonomiques des postes de travail à partir de données Kinect ", July 8, 2016 at Rennes 2 University.
- Invited member for C. Faure PhD Defense: " Analyse en réalité virtuelle de la coopération lors d'une interception de balle : interaction et interférence ", december 17, 2019 at Rennes 2 University.
- Participation to monitoring committees from G. Bonnet (Université Paris-Saclay), M. Gallot (Université Paris-Saclay), G. Levernier (Université Paris-Saclay), G. Millour (Université de Franche-Comté), O. Haj Mahmoud (Université Rennes 2), A. Hafs (Université Paris-Saclay), C. Thevenot (Université de Nancy), L. Martinez (Université Paris-Saclay), M.-P. Seba (Université de Paris), Y. Giovanelli (Université Reims Champagne-Ardenne).

Responsibilities

Co-leader of Research Axis untitled " Human Factors, Human/Machine Interactions " of MHAPS team into the CIAMS laboratory (with Dr. Thomas Deroche, from Sept. 2019): Animation, budget, thematical organization, HCERES overview writing, etc. Number of concerned colleagues: 15.

3.7 List of publications

International Journal Publications (peer-reviewed)

1. Karamanoukian, A., Boucher, J.-P., Labbé, R., Vignais, N. Validation of Instrumented Football Shoes to Measure On-Field Ground Reaction Forces. *Sensors*, 22, 3673, 2022. doi: 10.3390/s22103673.

2. Verdel, D., Sahm, G., Bastide, S., Bruneau, O., Berret, B., Vignais, N. Influence of the physical interface on the quality of human-exoskeleton interaction. *IEEE Transactions on Human-Machine Systems*, 1-10, 2022. doi: 10.1109/THMS.2022.3175415.

3. Verdel, D., Bastide, S., Vignais, N., Bruneau, O., Berret, B. Human Weight Compensation with a Backdrivable Upper-Limb Exoskeleton: Identification and Control. *Frontiers in Bioengineering and Biotechnology, section Bionics and Biomimetics*, 1396, 2022. doi: 10.3389/fbioe.2021.796864

4. Viseu, J.-P., Yiou, E., Vignais, N., Olivier, A. Postural Control Specificities According to Sports Expertise: A Comparison between Female Soccer Players, Horseback Riders and Non-Athletes. *Social Science Research Network*, preprint, 2021. doi: 10.2139/ssrn.3944521

5. Treussart, B., Caron, R., Geffard, F., Marin, F., Vignais, N. Personalizing the control law of an upper-limb exoskeleton using EMG signal. *BioRxiv,* preprint, 2021. doi: 10.1101/2021.09.23.461504

6. Treal, T., Jackson, P. L., Jeuvrey, J., Vignais, N., & Meugnot, A. Natural human postural oscillations enhance the empathic response to a facial pain expression in a virtual character. *Scientific Reports*, 11(1), 1-10, 2021. doi: 10.1038/s41598-021-91710-5

7. Verdel, D., Bastide, S., Vignais, N., Bruneau, O., Berret, B. An identification-based method improving the transparency of a robotic upper-limb exoskeleton. *Robotica*, 1-18, 2021. doi: 10.1017/S0263574720001459.

8. MacIntosh, A., Vignais, N., Desailly, E., Biddiss, E., Vigneron, V. A classification and calibration procedure for gesture specific home-based therapy exercise in young people with cerebral palsy. *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, 29, 144-155, 2021. doi: 10.1109/TNSRE.2020.3038370

9. MacIntosh, A., Desailly, E., Vignais, N., Vigneron, V., Biddiss, E. A biofeedback-enhanced therapeutic exercise video game intervention for young people with cerebral palsy: A randomized single-case experimental design feasibility study. *PLOS ONE* 15(6): e0234767, 2020. doi: 10.1371/journal.pone.0234767

10. Macintosh, A., Vignais, N., Vigneron, V., Fay, L., Musielak, A., Desailly, E., Biddiss, E. The design and evaluation of electromyography and inertial biofeedback in hand motor therapy gaming. *Assistive Technology*, 34(2), 213-221, 2020. doi: 10.1080/10400435.2020.1744770

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International Conference Publications (peer-reviewed)

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45. Bideau, B., Kulpa, R., Vignais, N., Brault, S. & Craig, C. Virtual Reality to investigate sport performance. *Proceedings of European Workshop On Movement Science (EWOMS)*, Lisbon, Portugal, 2009.

46. Bideau, B., Multon, F., Vignais, N., Kulpa, R., Bilavarn, J. Réalité virtuelle pour l'étude du duel gardien-tireur. *Proceedings of the Association des Chercheurs en Activités Physiques et Sportives (ACAPS)*, Paris, France, 2005.

National Conference Publications (peer-reviewed)

1. Jelti, Z., Lebel, K., Bastide, S., Leborgne, P., Slangen, P., Vignais, N. Effet de l'utilisation d'un dispositif d'assistance physique pour des mouvements impliquant des flexions de tronc. *ERGO'IA 2021*, Oct 2021, Bidart, France.

2. Caën, N., Olivier, A., Vignais, N. Innovation méthodologique en ergonomie physique pour la prévention des TMS : deux cas d'application au métier de sellier. *ERGO'IA 2018*. Biarritz, France, 3-5 of October, 2018.

3. Bastide, S., Vignais, N., Geffard, F., Berret, B. Adaptation de l'homme à l'interaction avec un exosquelette : une approche issue du contrôle moteur. Journée Exosquelettes - *GT1 "Robotique et Santé"*, organisée par le GDR STIC-Santé, Paris, 30th of Nov., 2017.

4. MacIntosh, A., Vignais, N., Cocchiarella, D., Kociolek, A., Keir, P. J. Modelling the index finger : a comparison of computational methods to assess joint loading with submaximal dynamic tasks. *Ontario Biomechanics Conference 2014*. Barrie, ON, Canada, 14-16th of March, 2014.

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6. Vignais, N., Bideau, B., Craig, C., Multon, F., Kulpa, R. & Bootsma, R. Évaluation de la perception du gardien de handball : mise en place d'un cadre de travail en environnement virtuel. *Proceedings of the 1st workshop of the Association Française de Réalité Virtuelle (AFRV)*, Paris, 2006.

3.8 Five most relevant publications

#1 Title	Influence of the physical interface on the quality of human-exoskeleton interaction
Authors	Verdel, D., Sahm, G., Bastide, S., Bruneau, O., Berret, B., Vignais, N.
Reference	IEEE Transactions on Human-Machine Systems, 2022
Abstract	Despite exoskeletons becoming widespread tools in industrial applications, the impact of the design of human–exoskeleton physical interfaces has received little attention. This study aims at thoroughly quantifying the influence of different physical human–exoskeleton interfaces on subjective and objective biomechanical parameters. To this aim, 18 participants performed elbow flexion/extension movements while wearing an active exoskeleton with three different physical interfaces: a strap without any degree of freedom, a thermoformed orthosis with one (translation) and three degrees of freedom (translation and rotations). Interaction efforts, kinematic parameters, electromyographic activities, and subjective feelings were collected and examined during the experiment. Results showed that increasing the interaction area is necessary to improve the interaction quality at a subjective level. The addition of passive degrees of freedom allows significant improvements on both subjective and objective measurements. Outcomes of this study may provide fundamental insights to select physical interfaces when designing future exoskeletons.

#2 Title	A classification and calibration procedure for gesture specific home-based therapy exercise in young people with cerebral palsy
Authors	MacIntosh, A., Vignais, N., Desailly, E., Biddiss, E., Vigneron, V.
Reference	IEEE Transactions on Neural Systems & Rehabilitation Engineering, 2021
Abstract	Movement-based video games can provide engaging practice for repetitive therapeutic gestures towards improving manual ability in youth with cerebral palsy (CP). However, home-based gesture calibration and classification is needed to personalize therapy and ensure an optimal challenge point. Nineteen youth with CP controlled a video game during a 4-week home-based intervention using therapeutic hand gestures detected via electromyography and inertial sensors. The in-game calibration and classification procedure selects the most discriminating, person-specific features using random forest classification. Then, a support vector machine is trained with this feature subset for in-game interaction. The procedure uses features intended to be sensitive to signs of CP and leverages directional statistics to characterize muscle activity around the forearm. Home-based calibration showed good agreement with video verified ground truths (0.86 ± 0.11, 95%CI = 0.93-0.97). Across participants, classifier performance (F1-score) for the primary therapeutic gesture was 0.90 ± 0.05 (95%CI = 0.87-0.92) and, for the secondary gesture, 0.82 ± 0.09 (95%CI = 0.77-0.86). Features sensitive to signs of CP were significant contributors to classification and correlated to wrist extension improvement and increased practice time. This study contributes insights for classifying gestures in people with CP and demonstrates a new gesture controller to facilitate home-based therapy gaming.

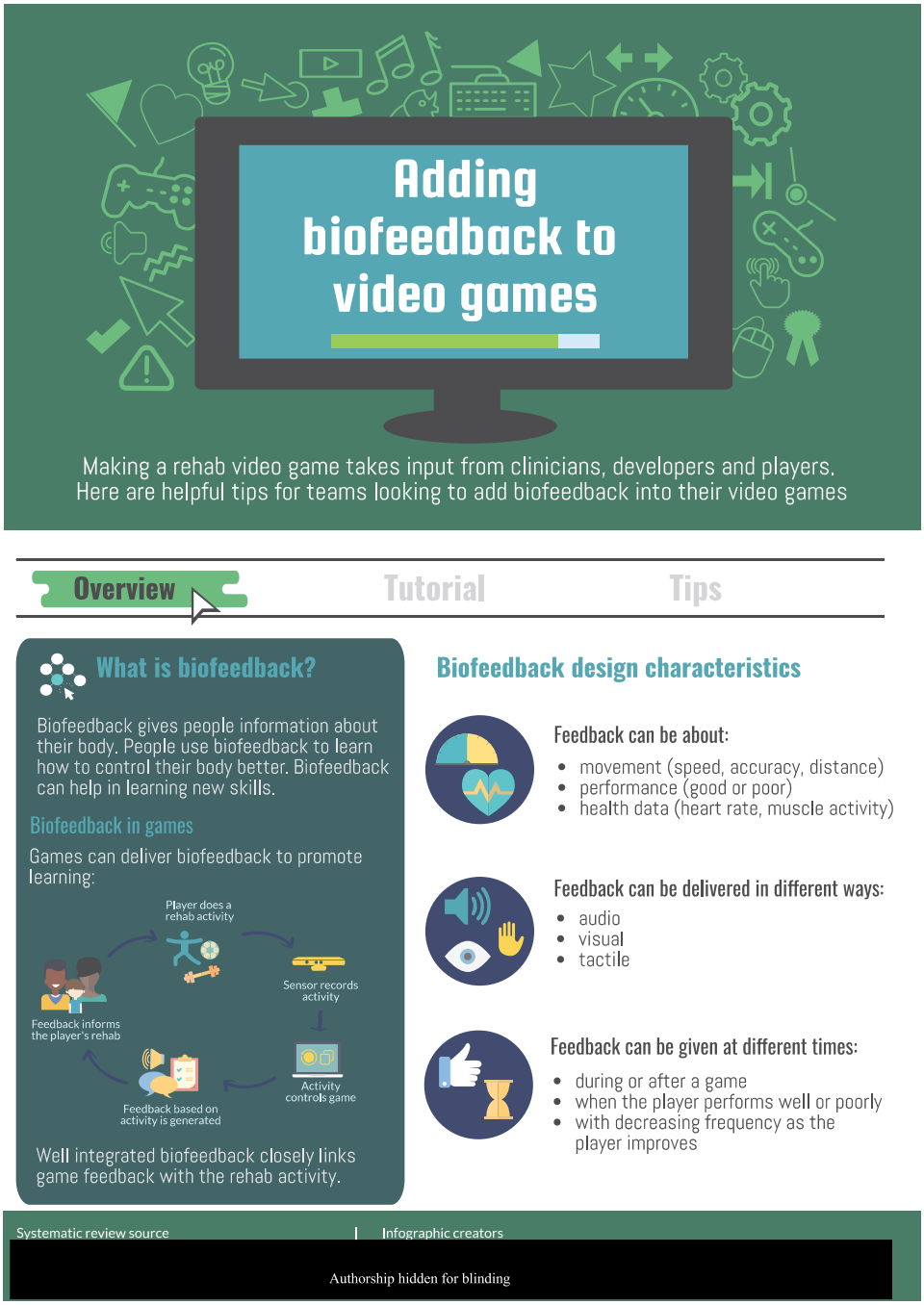
#3 Title	The design and evaluation of electromyography and inertial biofeedback in hand motor therapy gaming
Authors	Macintosh, A., Vignais, N., Vigneron, V., Fay, L., Musielak, A., Desailly, E., Biddiss, E.
Reference	Assistive Technology, 34(2), 213-221, 2020
Abstract	This article details the design of a co-created, evidence-based biofeedback therapy game addressing the research question: is the biofeedback implementation efficient, effective, and engaging for promoting quality movement during a therapy game focused on hand gestures? First, we engaged nine young people with Cerebral Palsy (CP) as design partners to co-create the biofeedback implementation. A commercially available, tap-controlled game was converted into a gesture-controlled game with added biofeedback. The game is controlled by forearm electromyography and inertial sensors. Changes required to integrate biofeedback are described in detail and highlight the importance of closely linking movement quality to short- and long-term game rewards. After development, 19 participants (8-17 years old) with CP played the game at home for 4 weeks. Participants played 17 ± 9 min/day, 4 ± 1 day/week. The biofeedback implementation proved efficient (*i.e.* participants reduced compensatory arm movements by 10.2 ± 4.0%), effective (*i.e.* participants made higher quality gestures over time), and engaging (*i.e.* participants consistently chose to review biofeedback). Participants found the game usable and enjoyable. Biofeedback design in therapy games should consider principles of motor learning, best practices in video game design, and user perspectives. Design recommendations for integrating biofeedback into therapy games are compiled in an infographic to support interdisciplinary knowledge sharing.

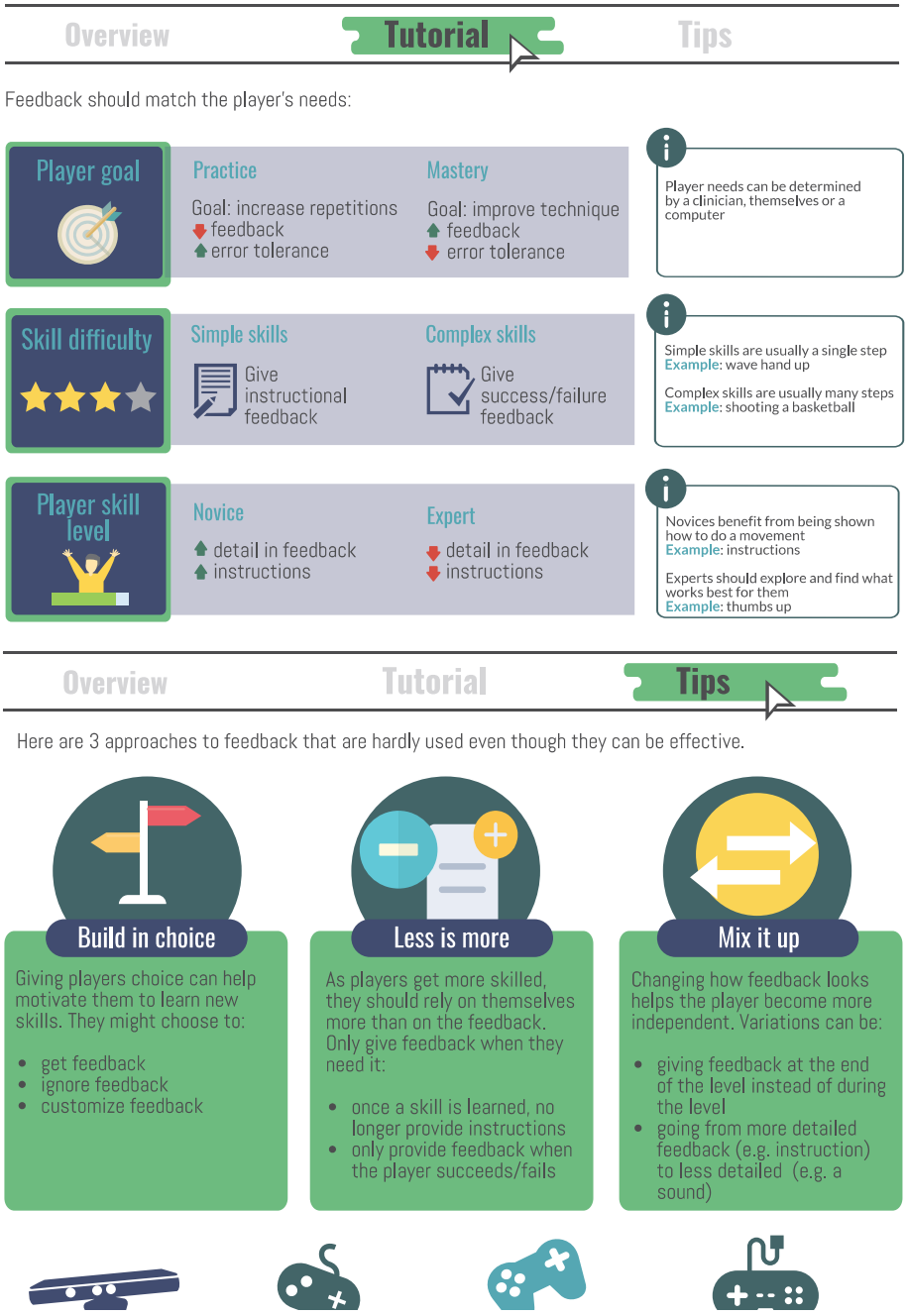
#4 Title	Physical risk factors identification based on body sensor network combined to videotaping
Authors	Vignais, N., Bernard, F., Touvenot, G., Sagot, J.-C.
Reference	Applied Ergonomics, vol. 75, 410-417, 2017
Abstract	Hand reaching and bipedal equilibrium are two important functions of the human motor behavior. However, how the brain plans goal-oriented actions combining target reaching with equilibrium regulation is not yet clearly understood. An important question is whether postural control and reaching are integrated in one single module or controlled separately. Here, we show that postural control and reaching motor commands are processed by means of a modular and flexible organization. Principal component and correlation analyses between pairs of angles were used to extract global and local coupling during a whole-body pointing beyond arm's length. A low-dimensional organization of the redundant kinematic chain allowing simultaneous target reaching and regulation of the center of mass (CoM) displacement in extrinsic space emerged from the first analysis. In follow-up experiments, both the CoM and finger trajectories were constrained by asking participants to reach from a reduced base of support with or without knee flexion, or by moving the endpoint along a predefined trajectory (straight or semicircular trajectories). Whereas joint covaried during free conditions and under equilibrium restrictions, it was decomposed in two task-dependent and task-independent modules, corresponding to a dissociation of arm versus legs, trunk, and head coordination, respectively, under imposed finger path conditions. A numerical simulation supported the idea that both postural and focal subtasks are basically integrated into the same motor command and that the CNS is able to combine or to separate the movement into autonomous functional synergies according to the task requirements.

#5 Title	Innovative system for real-time ergonomic feedback in industrial manufacturing
Authors	Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D. et Marin, F.
Reference	Applied Ergonomics, vol. 44(4), 566-574, 2013.
Abstract	This work presents a system that permits a real-time ergonomic assessment of manual tasks in an industrial environment. First, a biomechanical model of the upper body has been developed by using inertial sensors placed at different locations on the upper body. Based on this model, a computerized RULA ergonomic assessment was implemented to permit a global risk assessment of musculoskeletal disorders in real-time. Furthermore, local scores were calculated per segment, *e.g.* the neck region, and gave information on the local risks for musculoskeletal disorders. Visual information was fed back to the user by using a see-through head mounted display. Additional visual highlighting and auditory warnings were provided when some predefined thresholds were exceeded. In a user study (N = 12 participants) a group with the RULA feedback was compared to a control group. Results demonstrate that the real-time ergonomic feedback significantly decreased the outcome of both globally as well as locally hazardous RULA values that are associated with increased risk for musculoskeletal disorders. Task execution time did not differ between groups. The real-time ergonomic tool introduced in this study has the potential to considerably reduce the risk of musculoskeletal disorders in industrial settings. Implications for ergonomics in manufacturing and user feedback modalities are further discussed.

Appendix

Biofeedback Infographic


Adding biofeedback to video games
Making a rehab video game takes input from clinicians, developers and players. Here are helpful tips for teams looking to add biofeedback into their video games
Overview
Tutorial
Tips
What is biofeedback?
Biofeedback gives people information about their body. People use biofeedback to learn how to control their body better. Biofeedback can help in learning new skills.
Biofeedback in games
Games can deliver biofeedback to promote learning:
Player does a rehab activity
Sensor records activity
Activity controls game
Feedback based on activity is generated
Feedback informs the player's rehab
Well integrated biofeedback closely links game feedback with the rehab activity.
Biofeedback design characteristics
Feedback can be about:
movement (speed, accuracy, distance)
performance (good or poor)
health data (heart rate, muscle activity)
Feedback can be delivered in different ways:
audio
visual
tactile
Feedback can be given at different times:
during or after a game
when the player performs well or poorly
with decreasing frequency as the player improves
Systematic review source
Infographic creators
Authorship hidden for blinding


Overview
Tutorial
Tips
Feedback should match the player's needs:
Player goal
Practice
Goal: increase repetitions
feedback
error tolerance
Mastery
Goal: improve technique
feedback
error tolerance
Player needs can be determined by a clinician, themselves or a computer
Skill difficulty
Simple skills
Give instructional feedback
Complex skills
Give success/failure feedback
Simple skills are usually a single step
Example: wave hand up
Complex skills are usually many steps
Example: shooting a basketball
Player skill level
Novice
detail in feedback
instructions
Expert
detail in feedback
instructions
Novices benefit from being shown how to do a movement
Example: instructions
Experts should explore and find what works best for them
Example: thumbs up
Overview
Tutorial
Tips
Here are 3 approaches to feedback that are hardly used even though they can be effective.
Build in choice
Giving players choice can help motivate them to learn new skills. They might choose to:
get feedback
ignore feedback
customize feedback
Less is more
As players get more skilled, they should rely on themselves more than on the feedback. Only give feedback when they need it:
once a skill is learned, no longer provide instructions
only provide feedback when the player succeeds/fails
Mix it up
Changing how feedback looks helps the player become more independent. Variations can be:
giving feedback at the end of the level instead of during the level
going from more detailed feedback (e.g. instruction) to less detailed (e.g. a sound)

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Part II

Selection of full-text articles

A list of my articles can be found at
https://sites.google.com/site/nicolasvignaishomepage/publications

Ergonomic assessment based on on-body sensors

- Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D. et Marin, F. Innovative system for real-time ergonomic feedback in industrial manufacturing. Applied Ergonomics, vol. 44(4), 566-574, 2013.
- Vignais, N., Bernard, F., Touvenot, G., Sagot, J.-C. Physical risk factors identification based on body sensor network combined to videotaping. Applied Ergonomics, vol. 75, 410-417, 2017.

Biofeedback for motion optimization

- MacIntosh, A., Vignais, N., Desailly, E., Biddiss, E., Vigneron, V. A classification and calibration procedure for gesture specific home-based therapy exercise in young people with cerebral palsy . Transactions on Neural Systems & Rehabilitation Engineering, vol. 29, pp. 144-155, doi: 10.1109/TNSRE.2020.3038370.
- Macintosh, A., Vignais, N., Vigneron, V., Fay, L., Musielak, A., Desailly, E., Biddiss, E. The design and evaluation of electromyography and inertial biofeedback in hand motor therapy gaming. Assistive Technology, 1-9.

Human-Exoskeleton interactions

- Verdel, D., Sahm, G., Bastide, S., Bruneau, O., Berret, B., Vignais, N. Influence of the physical interface on the quality of human-exoskeleton interaction. IEEE Transactions on Human-Machine Systems, accepted. doi: 10.1109/THMS.2022.3175415.

Abstract

In the first chapter of this manuscript, my previous research projects are firstly synthesized. Based on the current context of musculoskeletal disorders which are considered as a critical public health issue, a conceptual five-step model for physical ergonomics is introduced (Model, Sensor, Analysis, Assessment, Intervention). This model serves as a basis for the first part of my previous research projects dedicated to physical ergonomic assessment using on-body sensors (electrogoniometers, inertial measurement units, etc.). As this assessment is also feasible in real-time, the second part of my previous research is submitted, by focusing on the use of continuous sensorial feedback, so called *biofeedback*, for human motion optimization. In a third part, the ergonomic intervention is presented in terms of physical assistance, by considering exoskeletons as a promising solution to prevent musculoskeletal disorders. The analysis of human-exoskeleton interactions thus allows to limit current issues and extents related to the use of these disposals.

In the second chapter of this manuscript, the five-step model for physical ergonomics permits to lay the foundation of my future research projects. These projects are including investigations on new methodologies for characterizing human motion, *e.g.* mecanomyography and embedded force sensors, both in sport and occupational environments. Developing methodologies for assessing passive exoskeletons in the field is also explored, as well as the improvement of human-exoskeleton interactions, which will allow forward definition of bioinspired control laws for active exoskeletons. These future projects are based on collaborations with both academic and professional partners.

Finally, the last chapter of this manuscript summarizes my academic activities and responsibilities, both at scientific level through publications and research grants, and pedagogical level through education initiatives and innovative pedagogical projects that have been funded.

Résumé

Dans le premier chapitre de ce mémoire, la synthèse de mes travaux de recherche passés est tout d'abord présentée. En se basant sur le contexte actuel des troubles musculo-squelettiques, véritable enjeu de santé publique, un modèle conceptuel d'ergonomie physique en cinq étapes est proposé (Modèle, Capteur, Analyse, Evaluation, Intervention). Ce modèle permet d'introduire la première partie de mes travaux de recherche dédiés à l'évaluation ergonomique à partir de capteurs embarqués (goniomètres, centrales inertielles, etc.). Cette évaluation pouvant s'effectuer en temps réel, la seconde partie de mes travaux de recherche est abordée, en se focalisant sur l'utilisation de retour sensoriel temps-réel, appelé *biofeedback*, pour l'amélioration du mouvement humain. Dans une troisième partie, l'intervention ergonomique est présentée sous l'angle de l'assistance physique, en considérant les exosquelettes comme une solution prometteuse de prévention des troubles musculo-squelettiques. L'analyse des interactions homme-exosquelette permet alors de circonscrire les enjeux et limites actuels liés à l'utilisation de ces dispositifs.

Dans le second chapitre de ce mémoire, le modèle d'ergonomie physique en cinq étapes permet de poser les bases de mes projets de recherche à venir. Ces projets incluent des investigations sur de nouvelles méthodes de caractérisation du mouvement humain, tels que la mécanomyographie ou les capteurs de force embarqués, que ce soit en environnement sportif ou professionnel. Le développement de méthodes pour l'évaluation des exosquelettes passifs *in situ* est également envisagée, ainsi que l'amélioration des interactions homme-exosquelette, ce qui permettra à terme la définition de lois de contrôle bioinspirées pour les exosquelettes actifs. Ces projets futurs sont basés sur des collaborations avec des partenaires académiques et professionnels.

Enfin, le dernier chapitre de ce mémoire résume mes différentes activités et responsabilités académiques, tant au niveau scientifique via les publications et subventions de recherche, que pédagogique à travers les enseignements effectués et les projets d'innovation pédagogique obtenus.