REFINEMENT OF EXOSKELETON DESIGN USING MULTIBODY MODELING: AN OVERVIEW

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ABSTRACT

Designing exoskeletons presents challenges related to multibody modeling, especially to improve the human-robot integration by optimizing the topology, the kinematics, and the inertia effects, and to get real-time feedback on the effort levels applied to the human body by the exoskeleton. In this context, the objective of this overview is to draw a state-of-the-art of existing issues and solutions with exoskeleton design using multibody dynamic modeling. First, this overview reveals that the modeling of exoskeleton architecture largely differs from one application to another in terms of design objectives and performances. The applications ranging from rehabilitating injured muscles to full assistance. Secondly, multibody dynamic modeling is seen as a powerful tool to design exoskeletons by simulating both the musculoskeletal system and exoskeleton dynamics, enabling one to predict the efforts performed by the exoskeletons and applied to the human body. Thirdly, designing a musculoskeletal model can improve our understanding of both the pathology and the best design to compensate it. Today, the main challenges are the identification of muscle actuation in a whole body model and to design exoskeletons that can provide help for rehabilitating patients in their everyday life movements.

Keywords: Exoskeletons, Design optimization, Virtual prototyping, Rehabilitation engineering

RAFFINEMENT DE LA CONCEPTION D'EXOSQUELETTES BASÉ SUR LA MODÉLISATION MULTICORPS: VUE D'ENSEMBLE

RÉSUMÉ

Concevoir des exosquelettes est encore une tâche ardue, du point de vue modélisation multicorps, spécialement pour améliorer l'intégration humain-robot en optimisant la topologie, la cinématique et les effets d'inertie dans la conception de l'exosquelette, et pour avoir un retour en temps réel sur les efforts appliqués au corps humain par l'exosquelette. Dans ce contexte, l'objectif de cette vue d'ensemble est d'établir un état de l'art des solutions et des problèmes existants en conception d'exosquelettes en utilisant la modélisation multicorps dynamique. Cette vue d'ensemble révèle d'abord que la modélisation de l'architecture d'un exosquelette diffère grandement d'une application à une autre en terme d'objectifs et de performance, les applications allant de la réadaptation de muscles blessés à une pleine assistance. Deuxièmement, la modélisation multicorps dynamique est un outil potentiellement puissant pour concevoir des exosquelettes en simulant à la fois le système musculo-squelettique et la dynamique de l'exosquelette, permettant ainsi de prédire les efforts appliqués par l'exosquelette sur le corps humain. Troisièmement, la modélisation multicorps peut améliorer notre compréhension à la fois des pathologies et aider à une meilleure conception pour compenser celle-ci. Aujourd'hui, les principaux défis sont l'identification de l'actionnement musculaire dans un modèle du corps complet et la conception d'exosquelettes pour la réadaptation.

Mots-clés : Exosquelettes, optimisation de la conception, prototypage virtuel, techniques de réadaptation.

1 INTRODUCTION

The main purpose of exoskeletons has evolved since the first one was built in 1963 [2]. They were initially thought to empower healthy men [2], more precisely soldiers, giving them extra strength and allowing them to carry heavy loads. This configuration can be defined as a master/slave interface where the soldier is the master controlling the exoskeleton that is the slave, thus providing extra strength. Later, the use of exoskeletons was rethought to assist people with disabilities, including active orthoses. The idea remains the same, giving the users extra strength, this time to compensate the lack due to pathologies or injuries. Exoskeletons are now also intended to improve rehabilitation for people with disabilities caused by strokes [3, 4], muscle disease [5], spinal cord injury [6], etc. Dehez et al. [7] and Galinski et al. [1] categorized the rehabilitation exoskeletons into two groups. On the one hand, there are exoskeletons that align with the human joints, where actuators are placed close to the joint, e.g. Fig. 1. On the other hand, there are self-aligning exoskeletons that mobilize the members on both sides of the joints directly and the actuator is free from being aligned with the human joint. Within the scope of this article, we focus on the first type of exoskeletons, whether it is portative like HAL-5 [8], BLEEX [9], or treadmill based like the Lokomat [10] and LOPES [11].

Safety is one of the top priorities when designing any kind of exoskeleton [6, 12, 13], as they interact closely with humans. One way to design and test an exoskeleton is to build two robots [14]. The first one is the inner robot, the master that simulates the human movements, while the second one is the exoskeleton that will be used by humans on the final actual world version. This was done in the past to find a safe way to test exoskeletons prior to their usage; if there is an unwanted dangerous torque on the inner robot then no human would get harmed.

Furthermore Galinski et al [1], stated that the two main criteria when designing exoskeletons for rehabilitation besides safety would be: 1. Range of motion and 2. Magnitude of parasitic efforts. These two criteria also define the difficulties encountered when designing exoskeletons matching human biomechanics. It is indeed difficult to identify the axis of the human joints, to reproduce all degrees of freedom and to avoid the relative motion between the exoskeleton and the human due to non-optimal fixation during exercise [7].

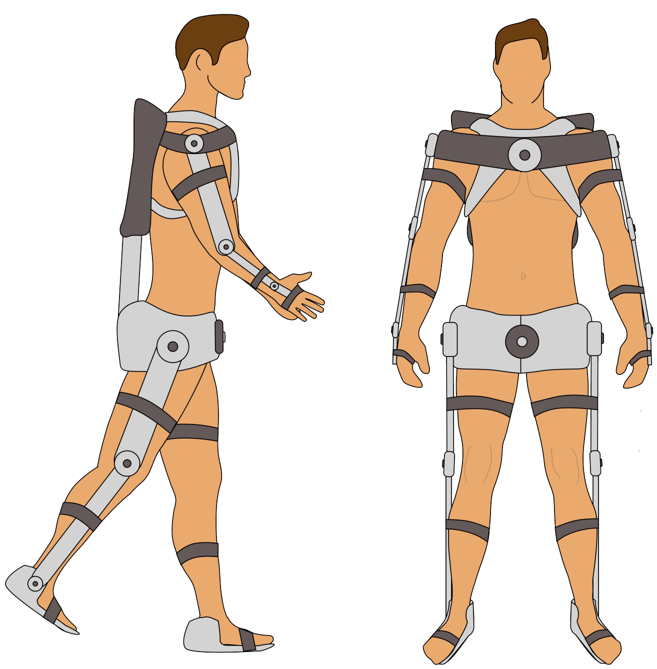

Fig. 1: Example of Exoskeleton where actuators are placed close to the joints.

Nowadays, exoskeleton testing can be performed virtually, using multibody modeling as shown in Fig.2 [1, 15]. In this context, multibody dynamic modeling can been seen as a powerful tool to design exoskeletons by simulating both musculoskeletal system and exoskeleton dynamics, enabling to predict in a non-invasive way the efforts performed by the exoskeletons and applied to the human body. For example, Laitenberger et al. showed that a realistic multibody model of the upper limb is necessary for the quantitative assessment of its joint kinematics and dynamics [16], announcing the possible application to exoskeletons [17]. In the context of this paper, multibody modeling concerns studies of the mechanisms from a kinematic and dynamic point of views. It also includes the musculoskeletal system as a rigid multibody system.

This study was carried out to assess the state-of-the-art survey on multibody dynamic modeling involved in the design process of exoskeletons for several projects at the "Chaire de recherche en génie de la réadaptation pédiatrique du Centre de réadaptation Marie Enfant, affiliated to École Polytechnique de Montréal [18-21]. Particularly, the specific objectives of this paper are to draw the first step into answering two main research questions:

1. How multibody modeling can help design exoskeletons?
2. What are the main challenges facing the design/research community?

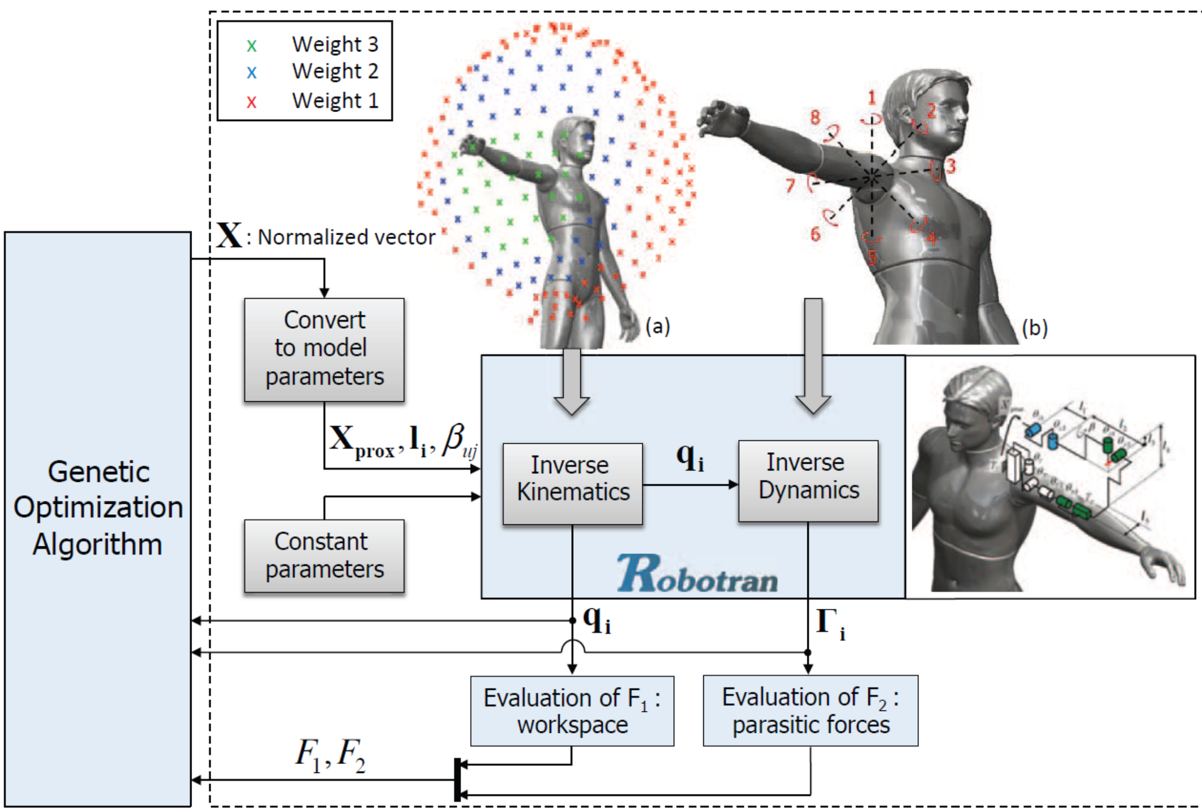

Fig. 2: Virtual optimization of an Exoskeleton of the shoulder, using Robotran, a multibody Software [1]. The two parameters that are being evaluated are the reachable workspace and the parasitic forces.

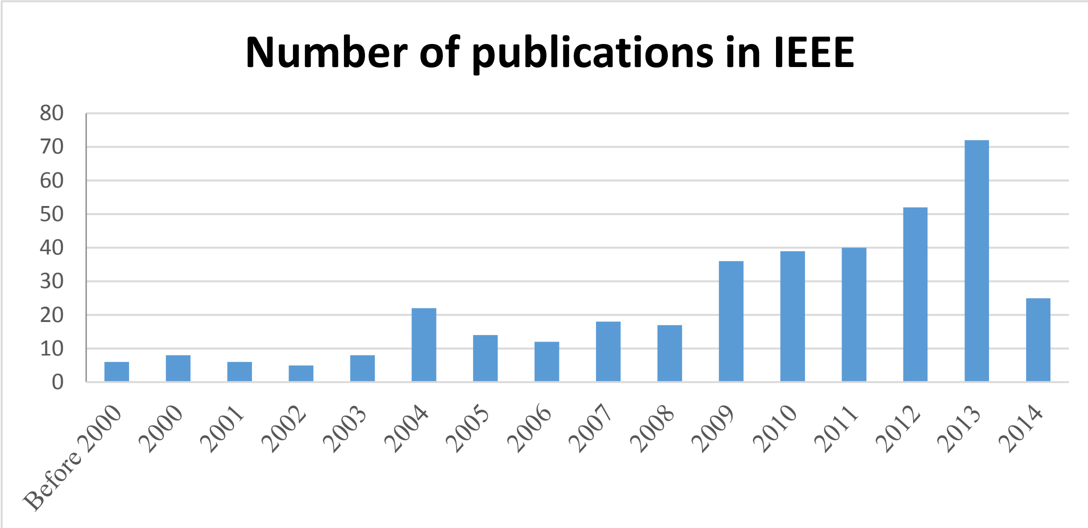

Fig. 3: Evolution of the number of articles/year. Source: IEEE-Xplore, Keywords: "exoskeleton", and the name of the software based on multibody modeling.

Fig. 43 shows the evolution of number of publications using the keywords "exoskeleton" along with the name of multibody software's or tools, ADAMS© (MSC Software ,USA), Opensim© (USA) SimMechanics© (Mathworks USA), AnyBody ModelingTM system (Anybody technology A/S, Denmark), Robotran© (CEREM, Belgium), Neweul-M2© (Universität Stuttgart, Germany), MBDyn© (Dipartimento di Scienze e Tecnologie Aerospaziali, Italy).

The number of studies involving multibody software to model and optimize exoskeletons has risen, especially over the last five years (see Fig. 3). The purpose here is not to compare the software solutions but to provide an overview of the evolution of multibody modeling for exoskeletons analysis. This evolution can be explained by the advantages that can provide multibody modeling regarding the exoskeleton design, presented in the next section.

2 ISSUES AND SOLUTION IN DESIGN OF EXOSKELETONS

2.1 Human musculoskeletal dynamics modeling for the design of exoskeletons

In order to fulfill the objectives of the exoskeletons in terms of effective human support, great attention must be paid to the biomechanics of the user. The state-of-the-art for lower limb exoskeletons presented by Dollar and Herr [3] showed that knowing the biomechanics of walking is important to build an exoskeleton that can operate along with the user with minimal chances of harm and in the most efficient way possible. To simplify computer calculation and to obtain the most natural movement from the exoskeleton, inverse kinematics of both the human body and the exoskeleton must be "identical" [22], i.e. in their study, Kim et al. explained that they consider the human arm to have 7 DoF, therefore the exoskeleton has 7 DoF. Then, criterion to solve the problem of muscle redundancy, covered in the next section, can be evaluated. Therefore virtually designing the exo-skeleton directly on a human-musculoskeletal model helps to constrain the exoskeleton kinematics to the human kinematics. Ferrati and Al [15], analyzed an existing exoskeleton by reproducing it virtually and constraining it to a human musculoskeletal model. Multibody modeling helped improving the kinematic design of the exoskeleton that was already physically improved numerous times since its creation in 1982. This framework is also encouraged by Agarwal and al. [23] claiming that carrying virtual design of an exoskeleton on human-based models allow to "introduce biomechanical, morphological, and controller measures to quantify the performance of the device".

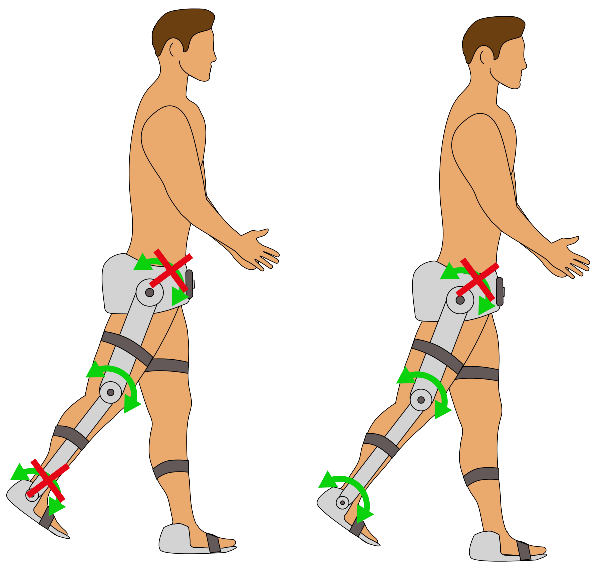

Fig. 4: Simplification Steps to solve the dynamics, first the ankle joint is locked (left) to solve the knee dynamics, then the ankle joint is added back.

The selection of DoFs is a crucial point in the exoskeleton design process. The human body is a really complex multibody system with numerous DoF and simplifications must often be made in order to design a viable exoskeleton. Beyl et Al [12] mentioned that before considering the design of a complete exoskeleton, it is important to reduce as much as possible the complexity of each sub-problem, e.g. for the lower limb, an early step was to lock the ankle joint to focus on the knee kinematics, and in the next step adding the DoF previously locked, illustrated in the Fig. 4. Similar simplifications of the human joints are often made in order to reduce the number of DoFs. However, these simplifications tend to impact the biomechanics of the exoskeleton as they don't represent fully the human articulation. This strategy is explained by Low [24] by the need "to achieve compact and power efficient design". Modeling can help to add new DoFs to improve the performance of the exoskeleton [15].

To control robotic devices, the classical multibody modeling of inverse kinematics is considered as a standard technique due to its simplicity and limited computation cost even for a high number of DoFs [25]. But nowadays, new optimal-control solvers of multibody systems, called Differential Dynamic Programming (DDP) [26], are more and more used (e.g.[27-29]) because of their simple yet efficient solving of direct implicit – called shooting – optimal-control problems, making it possible to control complex closed-loop systems, such as exo-skeletons or humanoid robots [27].

Design of robots that interact with the human body can be highly improved in terms of development time and movement effectiveness using multibody simulations. Furthermore, the multibody simulations can increase the knowledge about the human biomechanics.

2.2 Design for rehabilitation

Klein et al [4] reported that the rehabilitation of post-stroke patients using exoskeletons improves the ability to move the limbs. However, despite the encouraging results, the movement improvements achieved by rehabilitation exoskeletons, for patients who suffered from a stroke, are still small and do not match the daily movements complexity. To this effect, multibody modeling can help understand the human biomechanics, thus identifying the muscles that need most to be trained. For example, exoskeletons can be used to reinforce a specific muscle by applying forces and torques in the opposite direction to the patient movement thanks to a muscular limb model [30]. In their case study, Agarwal et al. [23] simulated the improvements of rehabilitation on a finger by testing the maximum allowable excitation constraint on the muscles. This means that the rehabilitation can be virtually quantified, and therefore several designs can be tested according to the injury. To virtually prototype exoskeletons on human musculoskeletal models opens the possibilities of custom exoskeletons for rehabilitation, as illustrated in Fig 5.

The musculoskeletal models include models of the muscles. Therefore, the use of inverse dynamics can help to quantify the muscle forces [31]. An application where muscles need to be specifically stimulated is the functional electrical stimulation (FES). Multibody modeling allows one to know how many DoFs are needed to facilitate stable standing using muscle activation., e.g. it was used to reduce the number of DoFs from 12 to 6 in the lower limbs in order to theoretically achieve stable standing (with FES) in paraplegic patients without asking them using their arms [32]. This result can be extrapolated to exoskeletons in order to minimize the number of DoFs for specific positions or movements reducing at the same time the size of the exoskeleton and the power needs.

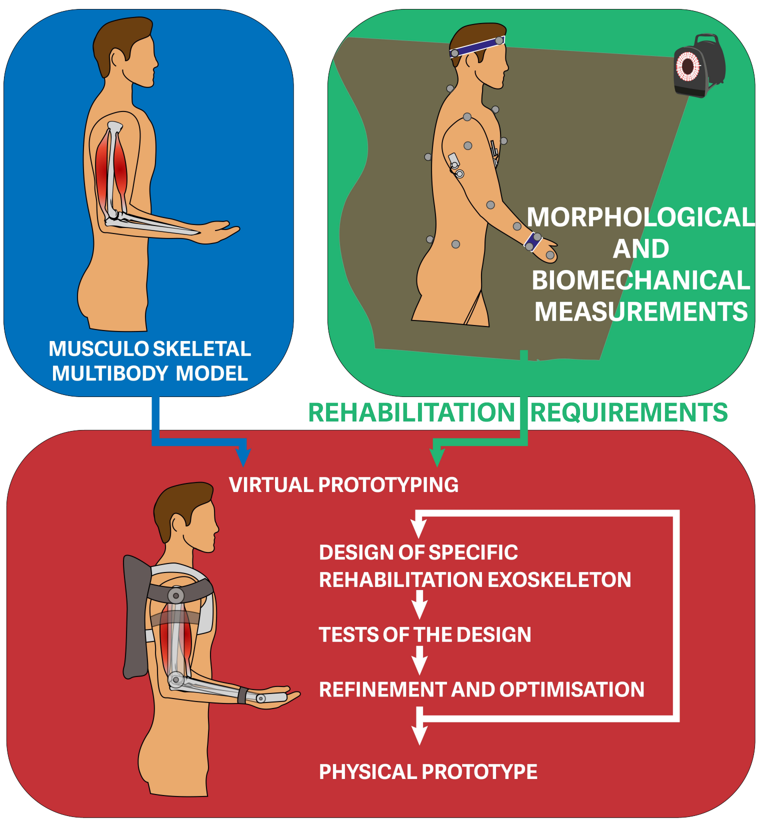

Fig. 5: Virtual prototyping process with musculoskeletal multibody model.

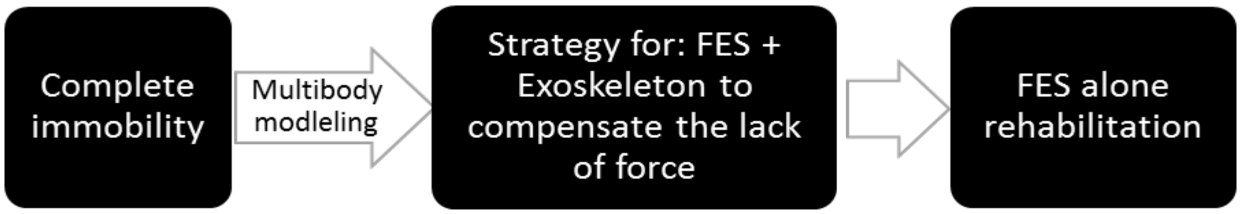

Fig. 6: Possible use of multibody modeling to design a combination of FES and exoskeleton as a transition step for FES alone rehabilitation.

Exoskeletons using FES is a combination currently studied [30, 32, 33] that could provide a smoother transition between complete immobility to FES alone rehabilitation, as illustrated in Fig. 6. In this case multibody modeling would allow both muscle identification and optimization of the number of DoFs.

3 DISCUSSION / CHALLENGES

This section describes the challenges that lie ahead for the design of exoskeletons using multibody modeling. The human biomechanics and modeling such a complex multibody system can be really challenging. But once this will be solved the next step will be to find a solution to mimic it in a best way. The first problem faced when modeling the human musculoskeletal system is that in the human body there are more muscles than joints leading to a difficulty to specifically identify the muscles acting on a specific range of motion. This is a recurrent problem in modeling the muscle contributions, called muscle redundancy [34-36]. Gallagher et al. [30] found a way to go around this muscle redundancy problem, their goal was to find a relaxed method that minimized the mean errors of the individual muscles between expected and desired muscle activation. The authors also mentioned the muscle pathologies diagnostic amongst the possibilities offered by their findings [30]. Their exoskeleton is designed to follow muscle patterns, but if used with the human fully controlling the movement, the exoskeleton can help find muscle disorders. Kim et al. [22] added that “resolving the human arm redundancy is critical to safe and effective interactions between humans and wearable robotic systems”.

As explained by Galinski et al [1], human joints “can rarely be considered as simple mechanical joints”. Agarwal et al. [23] explained that we still need to carry out experimental measurements in order to improve the model so it is more adapted to the user. Multibody modeling can help to understand the human biomechanics, but does not give directly the solution for the design of exoskeletons. We are still constrained by the actuators size and the need to have the lightest device possible [24].

Finally, a last parameter to take into account when modeling the body is the global center of gravity [37] for example Sharma and al. globalized the upper body as a generalized walker force instead of solely the dynamics of the upper body. They also explained the importance of simulating the model in a 3D environment, e.g. ankle moment happening in the lateral direction would be ignored if the simulation is only considered in the sagittal plane, and hence lacking biofidelity.

Modeling a mechanism using multibody dynamics is easier than modeling the human body, because joints, centers of rotation and inertial parameters are easily computed. The challenge is to improve models of the human body by adding realistic and exhaustive muscles models to improve biofidelity, while solving the muscle redundancy. Only then we can exploit the full advantages of designing exoskeletons that can improve our understandings of the biomechanics and improve rehabilitation.

4 CONCLUSION

The objective of this review was to identify issues and solutions of exoskeleton design and how multibody modeling can support the design activity. The review showed that modeling of exoskeleton architecture largely differs from one application to another in terms of design objectives and performances, the applications ranging from rehabilitating injured muscles to fully assisting the human user.

Secondly, multibody dynamic modeling can be seen as a potentially powerful tool to design exoskeletons by simulating both musculoskeletal system and exoskeleton dynamics, enabling to predict in non-invasively way the efforts performed by the exoskeletons and applied to the human body. Thirdly, designing a musculoskeletal model can improve our understanding of both the pathology and come up with the best design to compensate it.

As a perspective, musculoskeletal models need to be improved in terms of biofidelity and muscle redundancy resolution in order to become a reliable basis on which the design can be built. Therefore, there is an actual necessity to obtain a multibody model including all the muscles involved in specific movements. Developing this multibody model will face muscle redundancy issues which must be faced together with the challenges stemming from the biofidelity goals. This would help us obtaining a complete human musculoskeletal model where the muscle patterns are known and better understood. Achieving this can support the design of exoskeletons in a seamless and safe way and can also be used for specific muscle training.

Future research in exoskeletons modeling could refine muscle models allowing improving exoskeletons design and usage, ranging from medical rehabilitation and muscle disorder evaluation to sport training.

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