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Design-validation of a hand exoskeleton using musculoskeletal modeling

Clint Hansen[a,b], Florian Gosselin[c], Khalil Ben Mansour[a], Pierre Devos[a], Frederic Marin[a,*]

[a] Sorbonne Universités, Université de Technologie de Compiègne, UMR CNRS 7338, Biomécanique et Bioingénierie, Centre de Recherche Royallieu, F-60203, Compiègne, France
[b] Christian-Albrechts University of Kiel, Department of Neurology, 24105 Kiel, Germany
[c] CEA, LIST, Laboratoire de Robotique Interactive, F-91190 Gif sur Yvette, France

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ABSTRACT

Exoskeletons are progressively reaching homes and workplaces, allowing interaction with virtual environments, remote control of robots, or assisting human operators in carrying heavy loads. Their design is however still a challenge as these robots, being mechanically linked to the operators who wear them, have to meet ergonomic constraints besides usual robotic requirements in terms of workspace, speed, or efforts. They have in particular to fit the anthropometry and mobility of their users. This traditionally results in numerous prototypes which are progressively fitted to each individual person. In this paper, we propose instead to validate the design of a hand exoskeleton in a fully digital environment, without the need for a physical prototype. The purpose of this study is thus to examine whether finger kinematics are altered when using a given hand exoskeleton. Therefore, user specific musculoskeletal models were created and driven by a motion capture system to evaluate the fingers' joint kinematics when performing two industrial related tasks. The kinematic chain of the exoskeleton was added to the musculoskeletal models and its compliance with the hand movements was evaluated. Our results show that the proposed exoskeleton design does not influence fingers' joints angles, the coefficient of determination between the model with and without exoskeleton being consistently high ($\overline{R^2} = 0.93$) and the nRMSE consistently low ($\overline{nRMSE} = 5.42°$). These results are promising and this approach combining musculoskeletal and robotic modeling driven by motion capture data could be a key factor in the ergonomics validation of the design of orthotic devices and exoskeletons prior to manufacturing.

1. Introduction

Exoskeletons have considerably advanced in recent years and such devices are progressively reaching homes and workplaces. They can be used for various applications such as interactions with virtual worlds with the sense of touch, control of remote robots, rehabilitation, and assistance with daily activities (Bogue, 2009)– (Schiele and van der Helm, 2006). The development of exoskeletons is however still a challenge. As with other robots, they have to be designed for optimal performances in terms of workspace, speeds, accelerations, and forces. However due to the specific function of an exoskeleton it requires permanent contact and is tightly linked with the user. Consequently exoskeletons also have to be fitted to the user's anatomy and range of motion. From an ergonomic perspective, independent of its purpose and functionality, the most important requirement for an exoskeleton is its kinematic compatibility with the user's movements.

To meet this constraint, its number of degrees of freedom (DoF) and its compliance with the human anthropometry are key factors. Ideally, the external structure should not influence nor interfere with natural human movements (Privitera et al., 2017), and more specifically with those required to perform the targeted applications. To assess this, it is first required to describe in detail the tasks that must be performed with the exoskeleton. These tasks need to remain within the user's capabilities even when they wear the device. Indeed even if a given task appears to be rather simple, the user may not be able to perform this task if the exoskeleton does not match their actual anatomy. To validate this matching, the subject specific biomechanics need to be taken into account.

However, despite those obligations, exoskeletons are often developed using CAD models and their design is evaluated post-hoc (Cempini et al., 2014). The design is rarely based on the user's anthropometry but on the 50th percentile of an anthropometric database. Consequently, numerous physical prototypes are usually required to progressively meet the requirements. Designers rely on their experience to iteratively tune the device's dimensions and characteristics to find the best compromise for all users or at least for a given population (e.g. adult workers in industrial environments, teenagers playing videogames). Designing exoskeletons is thus a time consuming process with multiple

* Corresponding author.
E-mail address: frederic.marin@utc.fr (F. Marin).

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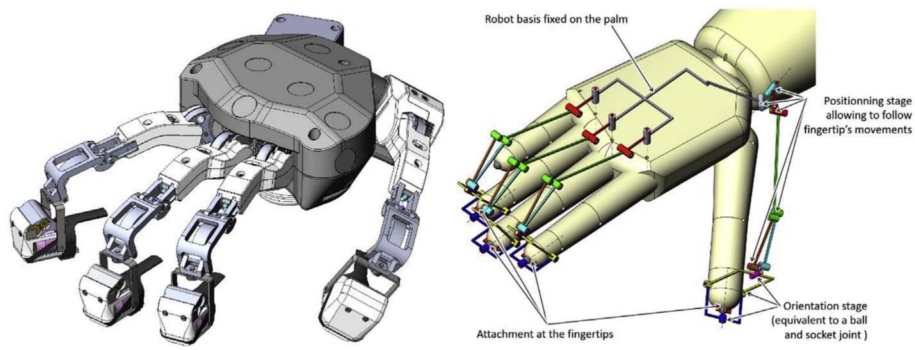

Fig. 1. The proposed MANDARIN hand exoskeleton design (left) and its kinematics (right).

iterations and physical prototypes from the initial idea to the final design.

In contrast to such approaches, the present study employs an in silico design validation methodology, i.e. to rely on fully digital models to guide and validate the design of an exoskeleton, with a focus on the hand. The hand is one of the most complex anatomical structures of the human body with visible anatomical variations among individuals in terms of digit length and bone shapes (Durand et al., 2011). In addition its numerous DoFs, small dimensions and the large mobility of each finger make it one of the most challenging body parts in terms of robotics and/or orthotics (Jones, 1997), (Grebenstein et al., 2012). Despite these difficulties, several hand exoskeleton prototypes have been developed (Heo et al., 2012), (Mozaffari et al., 2011), serving various purposes such as the creation and manipulation of virtual objects in virtual reality (VR) (Li et al., 2011), and the active movement assistance for rehabilitation (Martinez et al., 2013), (Yap et al., 2016). Systems are typically based on glove technologies or are modularly containing separate units for each phalanx. Indeed (Cempini et al., 2014), recently presented wearable exoskeletons that cover the DoFs and functionality of the hand. However, this system remains limited to two fingers, hence a relatively low risk of encumbrance of the exoskeleton during physical interactions. For such complex systems, in silico methods can orient the design earlier in the conception. This is particularly important for systems targeting four or five fingers.

Traditional in silico approaches used by the design and biomechanics communities however suffer from important limitations. Firstly, CAD software provide accurate models of the robot, but they usually integrate only simplified human models which do not reflect the high variability of limbs geometries and dimensions. Also, only simple tasks and scenarios are usually simulated compared to the complex activities found in homes and real factories. As a consequence, these tools do not precisely inform how the exoskeleton structure design influences the human movement characteristics for a given user and a given task. Alternately, human movement analysis (Nigg and Herzog, 2007) and musculoskeletal modeling (Vignais and Marin, 2014) propose relevant solutions and tools allowing to set-up user specific biomechanical hand models and to drive these models with task related movements. User-specific musculoskeletal models (Blasdel et al., 2012) based on imaging data (e.g. MRI, CT) (Valente et al., 2014) have shown their advantages over generic models and sensitivity analyses allow assessing model variations (e.g., (Gerus et al., 2013) (Hansen et al., 2014),). In turn, these tools do not, however, allow taking into account additional mechanisms such as exoskeletons. It quickly appears that both approaches are complementary and that robotic CAD modelling and biomechanics tools could be used in combination to solve the aforementioned shortcomings.

In this paper, we address this challenge by comparing biomechanically in silico hand movements of multiple users during two industrial assembly tasks with and without an exoskeleton. This approach allows meeting both the task and the human factor requirements (knowledge, behavior, abilities, and limitations) in the device development process (Privitera et al., 2017) to optimize human well-being and overall system performance in a prototype design.

2. Methods

2.1. Hand exoskeleton's design

The exoskeleton considered in this study aims to allow dexterous interactions with digital mock-ups in Virtual Reality (VR). Such digital environments progressively replace physical prototypes to test and validate the design and assembly feasibility of new systems without having to build physical mock-ups nor perform the task in real workshops or factories, saving space, time, and money. Also, workers can be trained in advance in VR, being fully operational as soon as they have to assemble or maintain the real system.

Here, we focus more specifically on the automotive industry. Among the new systems and procedures that will require training in the future, the maintenance of the batteries of electric vehicles are particularly challenging and were chosen as a representative use-case. After a careful analysis of the associated procedures, we selected 4 steps of the battery and other internal part disassembly. These tasks involve grasping and manipulation of small objects like nuts and cable connectors with the fingertips as well as the use of manual tools like pliers, screwdrivers, and socket wrenches.

Knowing that most of the hand environment interactions are achieved with the thumb, index, middle, and ring fingers (Gonzalez et al., 2014), a four fingers device with specific 6 DoFs kinematics chains for each finger was proposed (see Fig. 1. In order to fit all users, this device is attached to the palm and fingertips and runs in parallel with the hand without having its joints aligned with the user's ones. To allow efficient interaction with virtual environments, it should be able to apply forces up to 10N on the fingertips (Gosselin et al., 2013). To minimize its weight and bulkiness, we decided to use a single actuator to render the forces that occur when grasping a virtual object while fingertip haptic devices attached at the tip of the robots are used to deform the pulp to simulate the object's weight or texture.

Then the actuators, reducers, kinematics, dimensions and fingertip devices were optimized with a CAD software (Solidworks, Dassault Systems, Vélizy-Villacoublay, France) in order to allow maximum range of motion (all fingers can move in abduction-adduction and in flexion extension over a large range of motion and the thumb can be moved in opposition and placed in contact with all other fingertips) while minimizing the size and weight of the device as well as the space between the fingers and the exoskeleton.

As shown in Fig. 1, the CAD optimization was performed using a standardized hand model. Its dimensions were adjusted so as to correspond to the 50th percentile of the adult population, this percentile and associated dimensions corresponding to a subset of individuals whose anthropometric data are reported in the data bases from an anthropometric survey of American Army personnel (1987–1988) (Greiner, 1991).