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Article — Published Version

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Zeitschrift für Arbeitswissenschaft

Provided in Cooperation with:

Springer Nature

Suggested Citation: Auer, Simon et al. (2022) : Biomechanical assessment of the design and efficiency of occupational exoskeletons with the AnyBody Modeling System, Zeitschrift für Arbeitswissenschaft, ISSN 2366-4681, Springer, Berlin, Heidelberg, Vol. 76, Iss. 4, pp. 440-449, <https://doi.org/10.1007/s41449-022-00336-4>

This Version is available at:

<https://hdl.handle.net/10419/308445>

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Biomechanical assessment of the design and efficiency of occupational exoskeletons with the AnyBody Modeling System

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Accepted: 7 October 2022 / Published online: 26 November 2022
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Abstract

Exoskeletons were invented over 100 years ago but have only become popular in the last two decades, especially in the working industry as they can decrease work-related loads significantly. The most often used exoskeletons are for the lower back and shoulder since these are commonly affected body regions. All devices have in common that their purpose is to reduce internal loads of vulnerable body regions. Nevertheless, there is still little understanding on how biomechanical loading in the human body changes when exoskeletons are used. Therefore, further analyses are needed. A promising candidate for these are musculoskeletal models, which are based on an inverse dynamics approach and can calculate external parameters such as ground reaction forces or other interaction forces as well as internal parameters such as joint reaction forces or muscle activities. The various examples in the literature show that these models are increasingly used for assessing the biomechanical effects of exoskeletons on the human body. Furthermore, musculoskeletal models can calculate biomechanical loadings of humans with and without exoskeletons for all kinds of applications and allow an evaluation of their purpose.

Practical Relevance: This article highlights the possibilities of musculoskeletal models for assessing the design and efficiency of occupational exoskeletons. Several practical use cases are described along with distinct descriptions of common implications of musculoskeletal and exoskeleton modeling.

Keywords Inverse dynamics · Motion capture · Ergonomics · Biomechanics

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Biomechanische Bewertung von Design und Effizienz industrieller Exoskelette mit dem AnyBody Modeling System

Zusammenfassung

Exoskelette wurden vor über 100 Jahren erfunden, sind aber erst in den letzten zwei Jahrzehnten populär geworden, vor allem in der Arbeitswelt, da sie die arbeitsbedingten Belastungen erheblich reduzieren können. Am häufigsten werden Exoskelette für den unteren Rücken und die Schulter verwendet, da dies die am häufigsten betroffenen Körperregionen sind. Allen Geräten ist gemeinsam, dass ihr Zweck darin besteht, die internen Belastungen der gefährdeten Körperregionen zu verringern. Dennoch gibt es immer noch wenig Erkenntnisse darüber, wie sich die biomechanische Belastung im menschlichen Körper verändert, wenn Exoskelette verwendet werden. Daher sind weitere Analysen erforderlich. Ein vielversprechender Kandidat hierfür sind muskuloskelettale Modelle, die auf inverser Dynamik basieren und sowohl externe Parameter wie Bodenreaktionskräfte oder andere Interaktionskräfte als auch interne Parameter wie Gelenkreaktionskräfte oder Muskelaktivitäten berechnen können. Die verschiedenen Beispiele in der Literatur zeigen, dass diese Modelle zunehmend zur Bewertung der biomechanischen Auswirkungen von Exoskeletten auf den menschlichen Körper eingesetzt werden. Darüber hinaus können muskuloskelettale Modelle biomechanische Belastungen von Menschen mit und ohne Exoskelett für alle Arten von Anwendungen berechnen und eine Evaluation ihres Nutzens ermöglichen.

Praktische Relevanz: In diesem Artikel werden die Möglichkeiten von Muskelskelettmodellen für die Bewertung des Designs und der Effizienz von berufsbedingten Exoskeletten aufgezeigt. Es werden mehrere praktische Anwendungsfälle beschrieben und die allgemeinen Auswirkungen der Modellierung von Muskel-Skelett-Systemen und Exoskeletten erläutert.

Schlüsselwörter Inverse Dynamik · Motion Capture · Ergonomie · Biomechanik

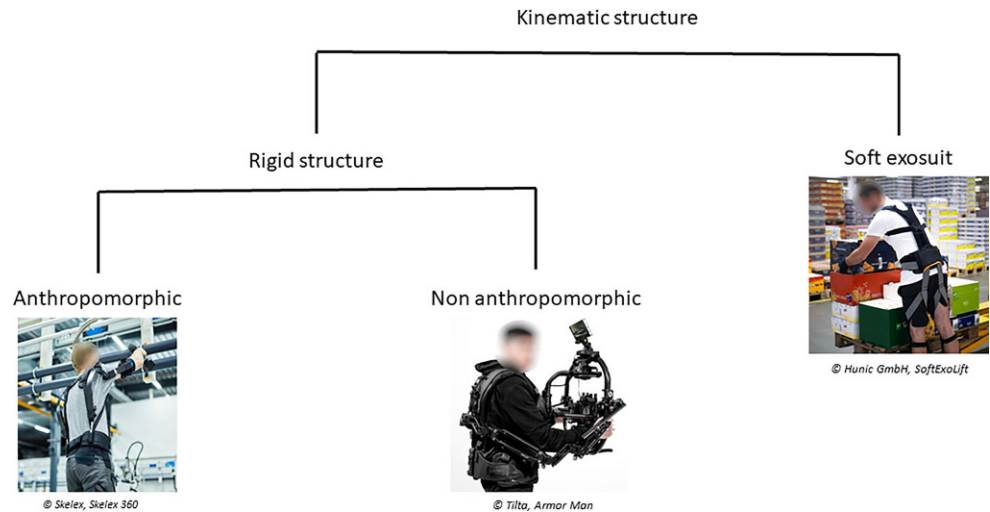
1 Introduction

Although the principle of exoskeletons is over 100 years old, their popularity has just begun to rise in the last two decades. Their fields of application reach from medical indications to military use to occupational utilization (Agrawal et al. 2017; Gull et al. 2020; Theurel and Desbrosses 2019). However, only in the last five to ten years they have become relevant in the working industry. The main driver of occupational exoskeletons is the prevention of musculoskeletal disorders and complaints to decrease work absence (Crea et al. 2021). Further, occupational exoskeletons improve the ergonomics and thereby the productivity of a manual workplace which is highly interesting for human-centricity (EU Commission 2021). The preventive efficacy is not yet evident (Steinhilber et al. 2020). Nevertheless, a recent longitudinal study proved that shoulder exoskeletons significantly decreased work-related shoulder health issues for selected overhead work tasks (Kim et al. 2022). Additionally, first studies claim that occupational exoskeletons can decrease cognitive load during work (Schroeter et al. 2020; Zhu et al. 2021). The implementation and evaluation of occupational exoskeletons can be complex and versatile, dependent on the scope and focus of the aimed application. Hoffmann et al. (2019) propose four dimensions to be considered for successful implementation and evaluation. Based on the exoskeletons' specifics, human capabilities, tasks and application context, a successful implementation is realized. A good understanding of the occupational situation for the problematic workplace is crucial for suc-

cessful implementation. Therefore, work ergonomists apply ergonomic assessment methods in advance to identify suitable workstations. Furthermore, exoskeleton adapted assessment methods still exist and can be applied to objectify the ergonomic impact of an exoskeleton (Fondazione Ergo-MTM Italia 2022). Methods in the field of digital ergonomics support systematic and efficient evaluation and implementation by considering all relevant aspects in the digital work model. In general, for a successful long-term implementation, it is important to involve all relevant stakeholders with condensed information fitted to their specific interests (Crea et al. 2021). Among other things (device usability, costs, perceived relief and discomfort etc.) it is important for most stakeholders, that an effective and safe utilization of exoskeletons in the workplace is guaranteed (Crea et al. 2021). Biomechanics of the human-exoskeleton interaction influence the redistribution of load and unloading of body areas and are thereby crucial to the devices' safety and effectiveness. Aside from long- and short-term experimental studies, musculoskeletal models could come in handy for simulation-aided exoskeleton development, optimization and evaluation and can be an important tool to quantify the effect of work-related loading and exoskeletons. Sophisticated biomechanical models help to objectify the biomechanical influences of person, exoskeleton and task specifics (Schmalz et al. 2022). Musculoskeletal models are digital human body models with the ability to calculate internal and external loads such as muscle forces, joint reaction forces, spine forces or ground reaction forces solely by the input of a given motion. These models allow the cal-

Fig. 1 Classification by kinematic structure for occupational exoskeletons based on Crea et al. (2021)

Abb. 1 Klassifizierung nach kinematischer Struktur für industrielle Exoskelette nach Crea et al. (2021)



culuation of e.g., spine loads during lifting. By introducing a mechanical model of an exoskeleton into such models, an objective comparison of use cases with and without exoskeletons can be done. Furthermore, interface forces, such as the contact forces between the exoskeleton and the human body can be investigated which is highly recommended for an objective comparison of different systems (Massardi et al. 2022). This enables the biomechanical assessment of real-life work tasks to a very detailed level. Since it is quite simple to create colourful pictures and graphs of any biomechanical loading with these models and it is quite hard to achieve reliable and robust results, the following sections shall provide an overview of the AnyBody Modeling System and its possibilities in biomechanically assessing occupational exoskeletons. The sections will provide a brief introduction to the state of the art of exoskeletons and musculoskeletal models as well as insights into the practical use of such models and the implications that come with them. The article aims to deliver an impression of the general subjects of exoskeletons and musculoskeletal modelling as well as the possibilities of different data acquisition methods. Furthermore, the basics of combined exoskeleton and musculoskeletal modelling are presented and discussed. The third objective is to provide a small overview of existing work regarding the design and efficiency of exoskeletons using musculoskeletal models.

2 State of the art of occupational exoskeletons and their assessment

The American Society for Testing and Materials (ASTM) International Technical Committee on Exoskeletons and Exosuits (ASTM F48) defined an exoskeleton “as a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity”. Moreover, Exosuits are

defined as similar in function but mainly consisting of soft and elastic structures (Lowe et al. 2019). Furthermore, occupational exoskeletons are devices that are applied to decrease biomechanical stress during manual strenuous work tasks like e.g., manual material handling or working in awkward postures. They can be classified via kinematic structure (cp. Fig. 1) and actuation type. Exoskeletons with a rigid kinematic structure can be anthropomorphic and non-anthropomorphic designed. In contrast, so-called exosuits have no rigid kinematic structure as they are transferring forces via elastic bands and structures that are closely worn on the human body. The actuation type of an exoskeleton can be classified as passive, semi-active or active dependent on the actuation principle. Passive systems are driven by passive elements like e.g., springs or damping elements, without the need of external energy. In semi-active systems, the support generating joints are also driven by passive force generating elements, but these can be actively adjusted e.g., by active spring-loading mechanisms. In active systems, the support generating joints are directly driven by electromechanical, pneumatic, hydraulic or any active other actuators (Crea et al. 2021).

Several devices exist to be applied for specific tasks by supporting highly strained body regions. The most prominent systems are back and shoulder exoskeletons that are mostly applied for manual material handling and overhead work (Theurel and Desbrosses 2019). The efficacy of occupational exoskeletons can be assessed with objective and subjective metrics. Objective metrics include bio signals that give insights into human metabolism, cardiac output and muscle activity. In addition, kinematics and kinetics with and without exoskeleton can give insights into how the device ergonomically works. Additional subjective metrics quantify the acceptance of the exoskeleton by the worker and how load and strain are perceived (Crea et al. 2021). Occupational exoskeletons raise in their fundamental function-

ality a complex biomechanical interaction between the human musculoskeletal system and the external device. Some devices redirect high forces around vulnerable body regions, other devices directly transfer forces to the ground and further devices optimize the human motion. All devices have in common that their purpose is to reduce internal loads of vulnerable body regions by following one or a combination of the described biomechanical modes of action. Hence, there is still lacking evidence on how the new loading with exoskeleton assistance does look like and if it is helpful or may raise further potential concerns.

3 Musculoskeletal modeling with the AnyBody Modeling System

The field of musculoskeletal models has grown a lot in the last two decades. There are many musculoskeletal modeling and simulation software. Among the most popular are OpenSim (Seth et al. 2018) and the AnyBody Modeling System (AMS) (Rasmussen et al. 2002). While OpenSim is open-source, the AMS itself is commercial software with an open-code model library, the AnyBody Managed Model Repository (AMMR), where users can use, modify, contribute new models for specific purposes but under a specific AMMR license. Both applications are (not solely) based on an inverse dynamics approach, where motion and external loading is put into the model to calculate internal forces such as, joint, muscle and interface forces, and potentially even predict ground reaction forces. Musculoskeletal models bear several advantages. They enable detailed insight

into the human body and its interactions with the environment without the necessity of additional instrumentation. E.g., one can measure spinal disc forces during thorax flexion even without motion capture data, solely by simulating the thorax flexion angle. However, driving these models with recorded motion data is the standard workflow for most applications to ensure the most realistic human kinematics and therefore reliable kinetic output. In practice, this means that human motion is recorded via some motion capture system and put into the musculoskeletal model together with optional anthropometric data. Depending on the application, anthropometric data of the model could be derived from different methods, e.g., linear scaling models, statistical models, or computertomographical images of bones for refined geometry if available. This input is used to calculate the internal and external kinematics and kinetics of the system and hence, the model delivers muscle and joint forces and other physiological parameters (Damsgaard et al. 2006).

3.1 Basics of musculoskeletal modeling

The models in the AMS (cp. Fig. 2) are based on rigid multi-body systems. Therefore, the models consist of rigid bodies (=bones), actuators (=muscles) and other important components (e.g., tendons and ligaments). The bones are connected via joints that represent the functionality of the anatomical human joints. The motion data is necessary to derive accelerations, and in combination with the body- and segment inertial parameters one can calculate the kinetics of the model. Important kinetic parameters are e.g., ground

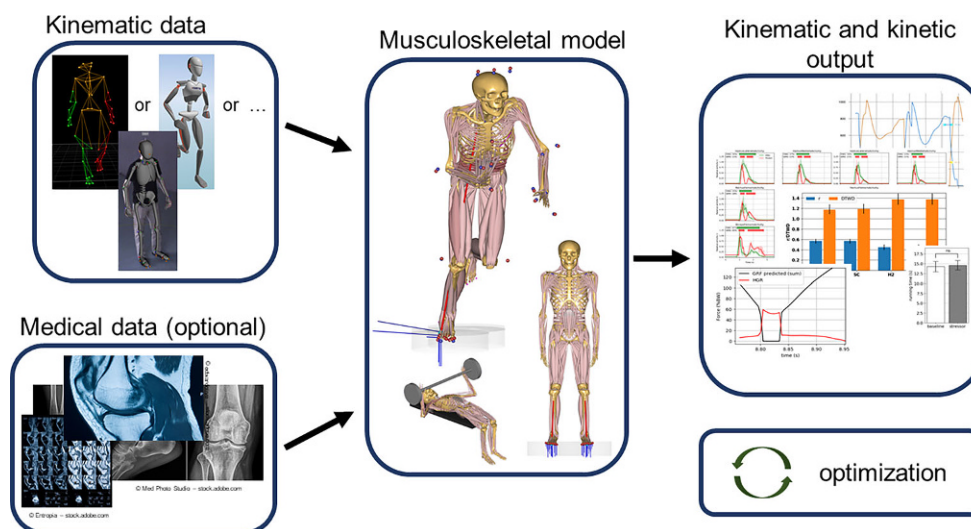


Fig. 2 Workflow of data acquisition and output calculation with musculoskeletal models. Kinematic data is used as input for the calculation of kinematic and kinetic parameters. Furthermore, medical imaging data can be added to the model's input to refine the boundary conditions

Abb. 2 Workflow der Datenaufnahme und Ergebnisberechnung mit muskuloskelettalen Modellen. Die kinematischen Daten werden als Input für die Berechnung der kinematischen und kinetischen Parameter verwendet. Zudem ist es möglich, dem Modell medizinische Bilddateien hinzuzufügen, um die Rahmenbedingungen zu verbessern

reaction forces, joint forces and moments and muscles activities and forces.

However, the human body is a complex system consisting of hundreds of muscles and bones interacting in many different, often ambiguous, and complex, configurations. Furthermore, the human body is a kinetically over-determined system since there are many more muscles involved in the movement than there would be necessary to balance the body's degrees of freedom (DOFs). The AMS approaches this problem mathematically by subjecting the boundary conditions, internal and external forces, and movements to an optimization problem, minimizing internal forces in respect of given motion and if applicable external forces. To calculate the kinematics and kinetics from the given input data, the musculoskeletal models represent human bones, muscles and ligaments mathematically. With this approach, the kinetics of individual body parts can be calculated (Damsgaard et al. 2006).

3.2 Kinematic data acquisition for musculoskeletal modeling

Normally, one wants to recreate real-life motion to analyze its resulting internal and external forces. The gold standard for this is marker-based motion capture (MMC) (Colyer et al. 2018). MMC uses reflective markers attached to the subject's skin (cp. Fig. 3a) and infrared cameras to trian-

gulate the positions and movements. Usually, the marker trajectories are transferred as a c3d data file into the musculoskeletal models. The models include the placed markers as virtual markers on the rigid bodies/bones and follow their movements. Hence, the musculoskeletal model moves just as the real-life subject does. MMC bears the advantage of being very accurate in terms of motion recreation (Windolf et al. 2008). Nevertheless, MMC requires a lot of effort from supervisors and test subjects to create reliable and accurate data. The acquired data is sensitive to actual marker positioning, marker dropouts and light and motion artifacts (Windolf et al. 2008).

Another way to record motion data is recording with systems based on inertial motion capture (IMC). They use inertial measurement units (IMUs) with an accelerometer, gyroscope and magnetometer attached to each segment (cp. Fig. 3b) to measure its movement. Since this approach is associated with an integration-based sensor drift, most systems use computer algorithms to account for that drift. Additional algorithms are necessary due to electromagnetic interference on the sensors. If not corrected by sophisticated algorithms, the use of IMUs in occupational environments can be tricky. Another drawback of these systems is that they are less accurate than MMC systems (Al-Amri et al. 2018; Blair et al. 2018; Karatsidis et al. 2019). Nevertheless, they allow a sufficient recording of many movements with an uncomplicated setup. However, their accuracy still depends on the type of application and only few systems deliver sufficiently accurate motion capture data.

With the advances in camera technology and artificial intelligence, video-based motion capture (VMC) gains relevance in biomechanics research. Although the different systems are all based on video camera recordings, the underlying motion detection algorithms differ in each case. They use algorithms for silhouette tracking, color tracking, or other dedicated algorithms. Usually, two or more algorithms are combined to enhance motion tracking. VMC systems have the advantage, that they don't require a lot of subject preparation. The subjects can be recorded as they are (cp. Fig. 3c), meaning they don't need any motion capture markers attached to their body or any special clothing, which significantly reduces the time required. Since this technology is relatively new in biomechanics research, there is little research on the accuracy of VMC in comparison to the state-of-the-art MMC. Nevertheless, initial studies indicate reliable accuracy (Kanko et al. 2021; Moro et al. 2022).

A big challenge for all motion capture systems is the integration of the environment. Many applications make use of various objects that have to be interacted with. For example, a simple box that has to be lifted or an exoskeleton worn by the subject. Normally, these objects also move relative to the subject and their motion has to be tracked separately.

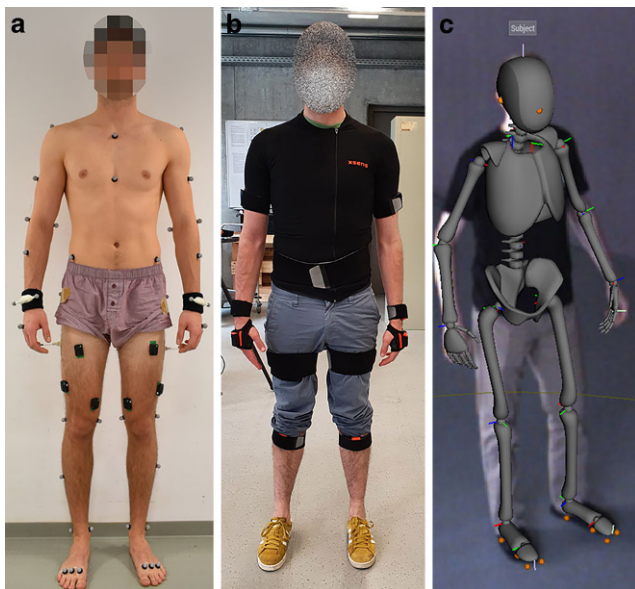


Fig. 3 Different motion capture setups. **a** Test subject equipped with a full-body marker set for MMC, **b** test subject with IMU sensors (orange) equipped for IMC recording and **c** test subject being tracked in a VMC system

Abb. 3 Verschiedene Motion Capture Setups. **a** Proband beklebt mit einem Ganzkörper-Markerset für MMC, **b** Proband bestückt mit IMU Sensoren (orange) für eine IMC Aufnahme und **c** mit VMC System getrackter Proband

MMC systems track these objects by simply attaching additional markers to the desired object. In IMC systems, the additional object usually has to be calibrated together with the subject, limiting the application possibilities. Furthermore, the number of additional IMUs is often limited by the system itself, resulting in a reduced recording setup for the additional object and possibly losing motion information. Generally, VMC systems are capable of tracking additional objects. However, they have to be trained to do so. Therefore, it might require some additional preparation of the VMC system to be able to track e.g., exoskeletons. Depending on the exoskeleton, it is possible that the motion of a subject wearing an exoskeleton cannot be captured, e.g., the exoskeleton may prevent the placement of markers on the subject. In such cases, it may be required to assume the motion of the subject from the recorded motion of the exoskeleton by adding kinematic constraints between the human and exoskeleton in the model.

In summary, there are three prevailing but different ways of acquiring motion capture data. They are based either on marker tracking, IMU sensors or video recordings. Each system has its advantages and disadvantages for the various fields of applications. While MMC still is the gold standard due to its accuracy, the utilization of IMC and VMC has increased and created new possibilities in motion capture practices.

3.3 Measurement and prediction of boundary conditions

Since musculoskeletal models reproduce in-depth human body parameters, it is essential to accurately determine the boundary conditions of the simulations to increase the calculations' reliability. One major aspect of boundary conditions is the determination of ground reaction forces (GRF). The default way of assessing them is to measure them via force plates in the ground. Musculoskeletal software is capable of taking these forces and moments as input and transferring these forces to the human model's feet. Although this method produces accurate boundary conditions, it only allows very few (usually two) and pre-defined measurement locations. In the field of sports biomechanics or occupational health, the subjects often have more than two positions, where ground reaction forces are relevant. In this case, the AMS features a ground reaction force prediction model (cp. Fig. 4). This means that the musculoskeletal software calculates the GRF solely via the given motion data and inertial parameters of the human body. This method has already been validated for various activities of daily living and sports and produces reliable forces and moments without the necessity of force plates (Fluit et al. 2014; Skals et al. 2017). This enables a much broader measurement volume and enhances the possible fields of

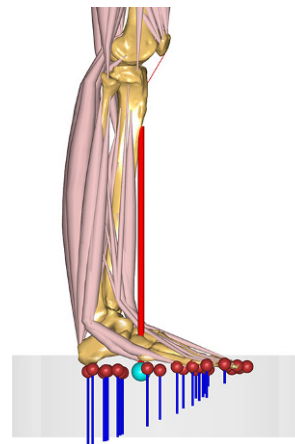


Fig. 4 Ground reaction force prediction model showing the resultant GRF vector (in red) and the center of pressure (in turquoise)

Abb. 4 Modell für die Bodenreaktionskraft-Prädiktion, welches den resultierenden Vektor der Bodenreaktionskraft (in rot) und den Druckschwerpunkt (türkis) anzeigt

application since the determination of GRF is possible at any time of the musculoskeletal simulation.

Similar characteristics apply to the measurement and prediction of interface forces and moments, such as contact forces of humans and their environment. Often humans have to interact with their environment when lifting objects or when sitting or lying. In these cases, the interface forces are important boundary conditions and have to be applied to the musculoskeletal models either by importing measured forces or by predicting these forces within the model. Usually, measuring interface forces is even more laborious than predicting them, because the load cells have to be applied in a way that they don't interfere with the actual motion capture recording, either by constraining the range of motion or by blocking the field of view of MMC and VMC cameras. Therefore, it is beneficial to predict these as rigid body contact forces, similarly as the GRF are determined. The AMS can compute these interface forces on multiple segments without the necessity of load cells. However, it is essential to provide the models with the right prerequisites for this. For example, if the contact forces between the pelvis and a chair will be calculated, the models require an accurate implementation of the seat in relation to the pelvis. For example, it is necessary to consider the correct distance and orientation of the two objects to each other, so that the kinematics and kinetics act in the right direction.

3.4 Fields of application and limitations

With the numerous possibilities of musculoskeletal models to reproduce boundary conditions and calculate distinct body parameters, they can be used for many applications. One of the first areas developed was orthopedics since the models allow an evaluation of many surgical techniques. For example, Weber et al. (2014) computed hip joint reaction forces for patients after conventional and minimally invasive total hip replacement surgery. They found that minimally invasive total hip replacement results in a greater

symmetry of hip joint reaction forces in absolute value as well as force orientation compared to conventional surgery. Benditz et al. (2018) computed spine joint reaction forces of 52 patients before and after spinal fusion surgery using musculoskeletal models. They determined increased spinal compression forces in patients with higher sagittal displacement after the surgery, although the shear stress decreased with sagittal imbalance. Simonsen et al. (2021) investigated changes in lower limb and foot mechanics between two types of foot orthoses. They calculated lower limb mechanics of 27 patients with rheumatoid arthritis with the AMS and found that custom-made foot orthoses reduced ankle flexion and eversion moments as well as the average forefoot pressure compared to prefabricated orthoses. These studies are just a small excerpt of hundreds of studies conducted in the field of orthopedics using musculoskeletal models. Another rising field of musculoskeletal model application is sports biomechanics. With the advances in motion capture, it is easily possible to acquire highly dynamic motion capture data and consequently calculate biomechanical loads during sports movements. Ali et al. (2014) used musculoskeletal models to investigate gender bias in non-contact ACL injury rate during single-leg landings. They analyzed hamstring, gastrocnemius, and quadriceps muscle force, GRF, and joint reaction forces of the lower limb. They found significant differences between genders in peak vertical GRF and the hip axial compression forces. Dupré and Potthast (2020) assessed hip joint kinematics and kinetics, and adductor muscle forces of pubertal soccer players with MMC and musculoskeletal models. Their results indicate a higher groin injury risk for these soccer players during peak height velocity due to changes in movement techniques. Additionally, in Auer et al. (2021), changes were found in muscle and joint forces of the lower limb after calculating the kinetics of change of direction maneuvers of 12 professional youth soccer players, when they were exposed to additional cognitive tasks while running.

Nevertheless, the models can only recreate movements and therefore only calculate internal forces based on these voluntary movements and lack accuracy due to several factors. These include the absence of e.g., intrinsic muscle activation due to stress or a missing representation of neural damage in the models. Hence, the investigation of non-kinematic parameters and their influence on biomechanical loading is limited.

Besides the already vast opportunities for the application of musculoskeletal models, there is still room for improvements. Hence Engelhardt and Melzner et al. (2020) developed, implemented and validated a fully detailed musculoskeletal hand model using the AMS. It provides validated muscle and joint forces of the forearm that can be used for practical applications. Hence, Melzner et al. (2021) performed a pilot and feasibility study on the biomechan-

ical loads of medical staff during real deliveries and on a birthing simulator with musculoskeletal models. They compared different positions and found lower average maximum load in kneeling posture. Further on, Aurbach et al. (2020) developed a new muscle wrapping algorithm for the musculoskeletal shoulder model. With their improvements to the shoulder joint geometry, they improved deltoid muscle activation and consequently shoulder joint reaction forces above 90° abduction. However, the shoulder model remains challenging in terms of biomechanical modeling, since they also found that joint reaction forces above 90° flexion are still underestimated by their model (Aurbach 2020).

4 Musculoskeletal simulations with exoskeletons

Since musculoskeletal models have the advantage of calculating interface forces without actually having to record them and determining various biomechanical parameters, they often are used to evaluate exoskeletons. Zhou et al. (2017) proposed a design optimization approach for two passive exoskeletons helping brachial plexus injuries. They optimized spring stiffnesses and compared maximum muscle activities while lifting with and without the exoskeletons using musculoskeletal models. With their approach, they managed to reduce the maximal muscle activity for C7 nerve lesions from 25 to 0.31% in their conceptual design. Jensen et al. (2018) developed and simulated a passive upper extremity orthosis for amyoplasia. They presented a prototype whose spring stiffnesses were optimized via musculoskeletal simulations of the exoskeleton for ten static postures during activities of daily living. As a result, they could reduce the average maximum muscle activity when the exoskeleton is worn. An interesting study by Shourijeh et al. (2017) found that hip aligned assistive torque is much more effective than ankle or knee aligned torque during box-lifting considering metabolic energy consumption. Tröster et al. (2020) designed an active occupational upper-limb exoskeleton based on using musculoskeletal models in the conceptual development phase. Therefore, they captured kinematic data with an experimental setup to reproduce working situations. They analyzed muscle and joint outputs of different body regions with and without a conceptual active exoskeleton. Their calculations revealed a significant relief potential in the lower back and shoulder area of the musculoskeletal apparatus. A similar approach, which made a conceptual analysis for a lifting task with different support torques around the shoulder supporting the upper arm and/or forearm, also highlights the benefits of model-based analysis using musculoskeletal models in the early design stage of exoskeleton developments (Gneiting et al. 2022).

Ishii and Takahashi (2021) evaluated and negated based on musculoskeletal modeling a potential negative effect of an exosuit on the lumbar spine, as from the first perspective the suit may add compression in parallel to the back extensor muscles. Further, they determined a suitable number of active artificial muscles for the exosuit design by finding a balance in assist effect, model-based quantified lumbar burden and cost performance. Chander and Cavatorta (2020) investigated the human-exoskeleton interaction forces at a curved interface for musculoskeletal models. For this purpose, they used the previously described method of ground reaction force prediction in combination with measurements from pressure mats to calculate interface forces. They found that the method adapted from the prediction of GRF is well suited for the calculation of interface kinetics. Fritzsche et al. (2021) assessed the efficiency of a commercial upper-limb exoskeleton with 12 subjects in an overhead task. The authors stated that the exoskeleton substantially reduces muscle activity and joint reaction forces in relevant body areas. Deltoid muscle activity and glenohumeral joint forces were lowered significantly. Nevertheless, such results have to be taken with caution, since some musculoskeletal shoulder models may underestimate JRF and consequently the associated muscle activities in shoulder flexion above 90°, depending on their muscle wrapping approach (Aurbach 2020). Bai et al. (2022) established a modular full-body exoskeleton and analyzed its performance using musculoskeletal models in a kinematic and kinetic study of 34 subjects. Although they could not find positive effects of their exoskeleton on biceps brachii and middle deltoid muscle activities for different lifting and carrying tasks in general, the subjects reacted very individually.

These studies show that using musculoskeletal models to assess exoskeleton efficiency is beneficial, especially in the early development and final implementation process of exoskeletons and furthermore state their advantages or—if given—the disadvantages. However, the assessment of exoskeletons with musculoskeletal models gets more ambitious for modeling human-to-exoskeleton interactions since distance and orientation to each other change over time due to changing acting forces and torques in the interface and interface stiffness characteristics. Those stiffnesses could be determined by the materials used for the exoskeleton, the fitting stiffness and the nature of the human soft tissue. Acting forces and torques in the interface result from the mechanical configuration of the exoskeleton (e.g. DOF) and joint misalignment as well as support torques, which influences the system's (dis)comfort characteristics (Jarrasse and Morel 2012; Massardi et al. 2022; Schiele 2009). They also lead to relative motion of the interface with respect to the body, thereby influencing its biomechanical efficacy (Damerau et al. 2015). With additional information on the potential relative movement of exoskeleton and skin, one can

calculate reliable interface forces for human-to-exoskeleton interactions. They depend primarily on the combined stiffness at the interface, i.e., the interaction between human soft tissue and deformable materials on the exoskeleton or seat. When these parameters are examined via practical experiments, they can be approximated in the model. In the absence of these parameters, rigid body contact force can be predicted at the interface. With additional information on the potential relative movement of exoskeleton and skin, one can estimate forces for human-to-exoskeleton interactions. Chander and Cavatorta (2020) received a good match with Center of Pressure (CoP) and the vertical force for modeling these contacts, but their mode required tuning of the strength of the contact elements, and it was only looking at rigid body forces. Hence, the distribution of force at the human-to-exoskeleton contact was not realistic, even though the CoP was reasonably accurate. Other approaches enhance the contact force results, e.g., finite-element analysis or contact force modeling taking foam, human soft and hard tissue into account, are possible but often much more costly. In summary, although musculoskeletal models do not yet provide all the human-exoskeleton interaction information, they are a valuable tool to assess the efficacy and effects of exoskeletons on the human body.

5 Conclusions and summary

The previous sections described the various fields of applications and implications of digital human body models and exoskeletons. Although the first concept of an exoskeleton has been around for over 100 years, it is only in the last 20 years that they have gained relevance, especially in workplace applications. Although the exoskeletons can support workers in their tasks, their primary aim is not to increase the maximum possible load lifted but to reduce the strain received by the user. Though, besides these positive effects, exoskeletons sometimes face complications regarding the acceptance of workers encouraged to use exoskeletons since wearing them is a new and unaccustomed situation. Furthermore, exoskeletons often restrain some degrees of freedom in human movement, making the application feel odd. Nevertheless, their benefits have already been stated for a small number of use cases and the use of passive and active exoskeletons still is rising.

Musculoskeletal models bear the possibility to calculate distinct and holistic muscle activities and forces, GRF as well as forces of interactions with the environment through a given motion. Furthermore, they offer possibilities to approximate the human energy expended based on physical work as metabolic cost (Arones et al. 2020; Koelewijn et al. 2019), which is an interesting performance indicator during manual material handling (Crea et al. 2021). Nevertheless,

they always are a simplified version of the human body and therefore have some limitations. E.g. in the current state, it is demanding to calculate reliable shoulder kinetics for overhead tasks, since the deltoid muscle wrapping is improper for these postures. The various examples in the literature show that these models are increasingly used for assessing the biomechanical effects of exoskeletons on the human body. Although some interface reactions are hard to determine, the models offer some ways to accurately set the boundary conditions. Hence, musculoskeletal models can calculate biomechanical loadings of humans with and without exoskeletons for all kinds of applications and allow an evaluation of their purpose.

Funding Open Access funding enabled and organized by Projekt DEAL.

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