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A Musculoskeletal Human Model-Based Approach for Evaluating Support Concepts of Exoskeletons for Selected Use Cases

C. Molz [1,✉], Z. Yao [2], J. Sänger [3], T. Gwosch [3], R. Weidner [2,4], S. Matthiesen [3],
S. Wartzack [1] and J. Miehling [1]

[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany, [2] Helmut Schmidt University, Germany,
[3] Karlsruhe Institute of Technology, Germany, [4] University of Innsbruck, Austria
✉ molz@mfk.fau.de

Abstract

This paper presents an approach for evaluating exoskeleton support concepts through biomechanical analyses on a musculoskeletal human model. By simplifying the support forces of an exoskeleton as external forces, different support concepts can be biomechanically evaluated for the respective use case without concrete design specifications of the exoskeleton. This enables an estimation of the resulting relief and strain on the human body in the early stages of exoskeleton development. To present the approach, the use case of working at and above head height with a power tool is chosen.

Keywords: user-centred design, design optimisation, supportive technologies, musculoskeletal human model, exoskeleton

1. Introduction

Exoskeletons have potential applications in the workplace for reducing the risk of work-related musculoskeletal disorders. Exoskeletons are wearable and interact very closely with the human body. Thus, a comprehensive biomechanical understanding of the human motion in the target use case is essential for a successful design of the exoskeleton. It helps to identify not only the demand of support for the selected application, but also the potential benefits and risks of an exoskeleton design.

In this purpose, biomechanical experiments are widely used in the development of exoskeletons, especially for the specification of requirements and the evaluation (Argubi-Wollesen and Weidner, 2018; Otten *et al*., 2018; Yao *et al*., 2019). However, some responses of the human body such as joint reaction forces and joint moments are very difficult to measure. Additionally, biomechanical experiments to find the optimal design parameters, such as force application points or force curves, are restricted and time consuming. Thus, musculoskeletal human model (MHM) based biomechanical simulation is an expedient and effective extension for biomechanical experiments in labs and may play an important role in the development of exoskeletons.

On the one hand, MHMs can be used to estimate the effects of support systems by testing their working principles with the MHM prior to design development. For example, (Miehling *et al*., 2018) demonstrated the potential positive effects of knee support during lifting movements by applying an abstract moment to the knee. On the other hand, MHMs also offer the potential to simulatively validate the utility of existing exoskeletons or to perform parameter studies to optimize existing designs. A MHM-based biomechanical study in AnyBody Modeling System (AMS) evaluated a commercially available shoulder-exoskeleton and its results widely agree with the results of a previous lab study (Fritzsche *et al*., 2021). Some works presented biomechanical evaluation of the exoskeleton design and control based on the MHMs. A MHM from OpenSim was used to optimize the actuator control and kinematic design of a lower-limb exoskeleton from previous work (Ferrati *et al.*, 2013). To improve the design of a lower-limb exoskeleton, especially its joint mechanics, two MHMs were built in AMS (Fournier *et al.*, 2018). A simulation-based approach is presented to identify the optimal design parameters of an upper-limb exoskeleton (Zhou *et al.*, 2017). Another contribution describes a individualized biomechanical simulation to optimize control parameters of a lower-limb exoskeleton based on a MHM (Khamar *et al.*, 2019). To optimize design parameters of an upper-limb exoskeleton for healthcare activities, a MHM from AMS was utilized to analyse the physical stress of the activities and to evaluate the proposed design (Tröster *et al.*, 2020).

In summary, there are already different approaches to investigate the effect of support systems like exoskeletons. However, these usually involve evaluating and optimizing existing design concepts of exoskeletons. A consideration of the need for support and the evaluation of different support approaches without existing design concepts is therefore not possible with these approaches. Other approaches look more closely at support needs, but represent support options in such an abstracted way that it is difficult to derive design concepts from them.

2. Approach for identifying potential of support concepts

Consequently, we present an approach for identifying the physical stress in a selected use case as well as to evaluate potential concepts of support for it in the pre-design phase by using biomechanical simulation. The procedure of the presented approach is depicted in Figure 1. Firstly, the use case is selected and experimental data for a biomechanical simulation are collected. By using a MHM a biomechanical simulation is conducted to analyse the load situation based on the use case. Here, support potential can be identified. Subsequently, support concepts are established, which define the support in terms of external forces on the body, without including more concrete design information of the support systems. Due to the variance of the application points, the direction and the profile of the support forces several generic support concepts can be descripted. The effects of the support concepts in the body can be estimated by using biomechanical simulation with MHM and serve as a basis for the further design elaboration of promising support concepts.

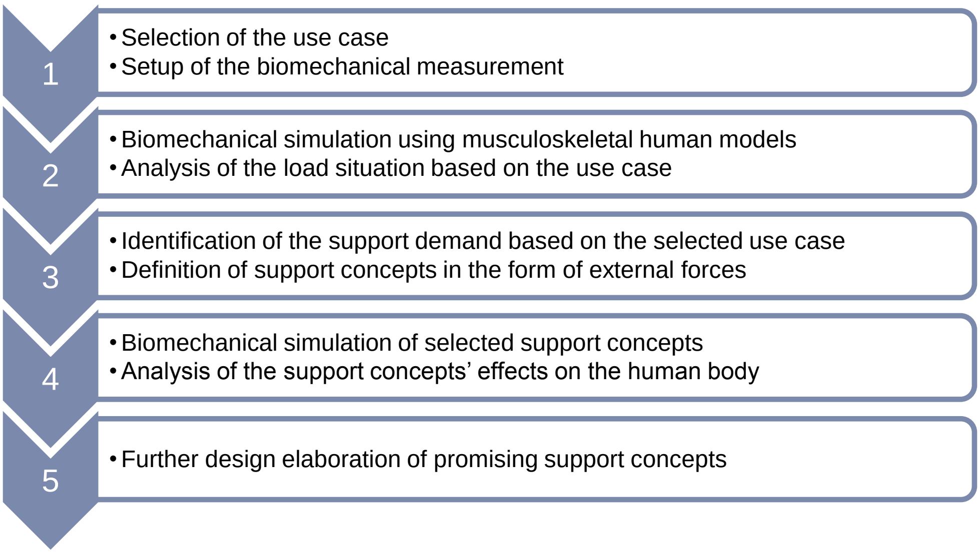

Figure 1. Procedure of the approach for identifying the potential of support systems using musculoskeletal digital human models in the early phases of product development

In the following, the individual steps of the presented approach are described by using the use case working at and above head height with a power tool.

2.1. Selection of the use case and setup of the biomechanical measurement

The selected use case should represent the usage behaviour of the user in the real application and at the same time be conducted under defined conditions. Field studies offer the advantage of observing the user in a real environment (ISO/TR 16982). The transfer of real applications into use cases, which can then be investigated more easily under laboratory conditions is methodically supported by Matthiesen et al. (2018). Under laboratory conditions, use cases can then be observed with more measurement technology like motion capture.

In this contribution, the use case working at and above head height with a power tool is chosen. This use case depicted a simplified task from the construction sector for ceiling installations and is characterized by the high load for the user's upper extremities (Linaker and Walker-Bone, 2015). To record the selected use case in laboratory, a representative task was defined as follows: Attaching a wood component (with a size of 50 mm x 50 mm x 10 mm with central borehole) with a screw (5 mm x 60 mm Torx) to a wooden board above head level by using a cordless screwdriver. The height of the wooden board to the participant is adjusted to ensure a shoulder elevation in the range of 0 ° to circa 120 ° in the right arm during the task. The task is defined by four sections, depicted in Figure 2: First, the participant holds a cordless screwdriver in the right hand and grasps a piece of wood with the left hand from a desk in front. Afterwards, the participant rises both hands to the wooden board above the head. In step three, the participant positions the piece of wood at the previously defined position with the left hand and sets a screw with the screwdriver in the right hand. After ending the screw-in process, the subject lowers both hands again. The whole task is completed in 10 seconds. The participant repeats the task 10 times in direct succession. A 29-year-old male participant with a body height of 180 cm was chosen for data collection. There were no known musculoskeletal disorders in the shoulder and arm region.

During the experiment, the movements of the test person were precisely recorded by using the optical motion capture system Vicon (Vicon Bonita, Oxford Metrics Ltd, UK). With the help of a force plate (AMTI OPT, 464 x 508 mm, Advanced Mechanical Technology Inc., USA), the resulting ground reaction forces and moments were deduced. In order to better evaluate muscle activations, which are later simulated with the human model, surface electromyography (sEMG) (Myon 320, 1.000 Hz, Myon AG, Schweiz) was recorded. For this purpose, the sensors were attached to muscles of the right arm, right shoulder and back. In this region, increased activation of the muscles is expected due to the work at and above head height with a power tool in the right hand.

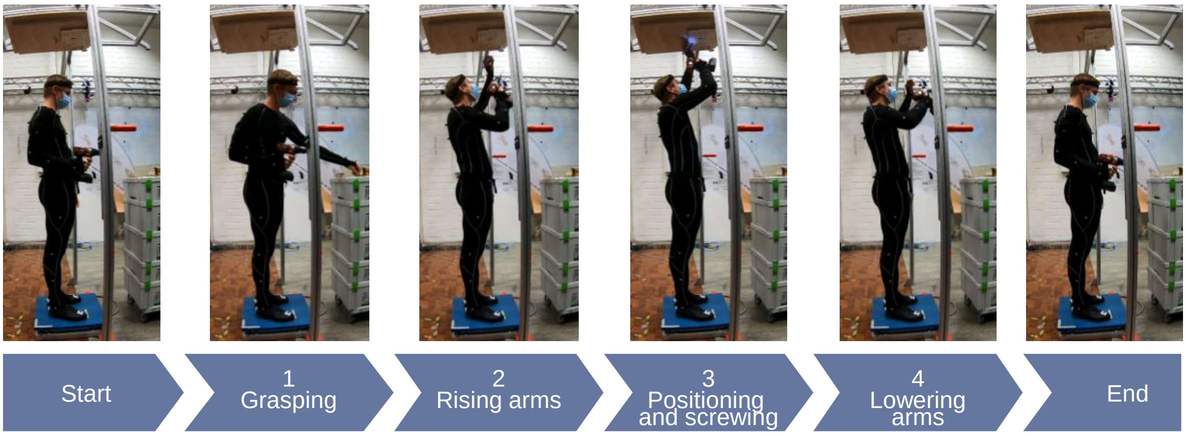

Figure 2. Movement sequence of the selected use case working in and above head height with a power tool

2.2. Biomechanical simulation and analysis of the selected use case

In order to evaluate the load on the user during the execution of the presented task, biomechanical simulations are conducted with a MHM. For this purpose, the simulation of user-product interactions using MHMs, as well as the general implementation for the presented approach, will be described in the following. Subsequently, the implementation and conduction of the biomechanical analysis for the selected use case will be presented.

2.2.1. *Modelling and simulation of user-product-interactions*

MHMs define the human musculoskeletal system as a rigid multibody system. The human skeleton is represented by rigid bodies, which are connected by joints. The degrees of freedom of the joints are defined in such a way that they correspond as closely as possible to human physiology. With the help of actuators following the Hill model (Hill, 1938; Zajac, 1989), the bones of the model are connected and thus muscle paths are mapped. By scaling these models, both concrete test subjects and user groups can be mapped (Miehling, 2019). While these models are originally used for motion analysis, there are now also approaches to their use for operation planning (Scherb *et al.*, 2020) or mapping of user-product interactions in the product development process (Wolf *et al.*, 2019).

The most common approach for conducting biomechanical analyses using MHMs is the application of inverse kinematics and inverse dynamics. For this purpose, movements are classically recorded in motion laboratories using motion capture methods. Subsequently, the joint angle curves of the human model are determined by means of an optimization problem so that the resulting motion corresponds as closely as possible to the recorded data. Thereafter, using inverse dynamics methods, forces and moments resulting from the motion and possible external forces can be determined. These in the form of joint reaction forces or muscle activations can then be used to evaluate the load on the human body.

For implementing the presented approach for a MHM based evaluation of support concepts for exoskeletons, we use the software OpenSim, an open source tool for musculoskeletal simulation (Delp *et al.*, 2007). In order to make the method accessible to a large number of use cases and support concepts, a whole-body model (Miehling, 2019) is used. This also allows the consideration of the effects on the whole body, caused by the use case as well as by possible support concepts. In the implementation of the approach, all forces acting on the human being are introduced into the MHM as external forces. This applies to all forces that relate to the support concepts, such as the support force but also the weight of the support system. Forces that arise due to the selected use cases are also introduced as external forces to the MHM.

2.2.2. *Biomechanical analysis of the load situation in the selected use case*

For the simulation of the load situation and its analysis, an exemplary cycle of the recorded movement for the use case was chosen. It reflects the selected motion pattern (grasping, rising arms, positioning and screwing, lowering arms). This motion was transferred to a whole-body model (Miehling, 2019) using the inverse kinematics method. In order to evaluate the human stress based on the use case, methods of the inverse dynamics were applied. For this purpose, the simulation is extended by external forces, which represent the weight of the power tool but also a generic process force as shown in Figure 3. Consequently, a force of 20 N resulting from the weight of the power tool was assumed as well as a process force of maximal 60 N during the screwing process. This motion sequence and external forces thus define the *baseline scenario*, without further support concepts for the user.

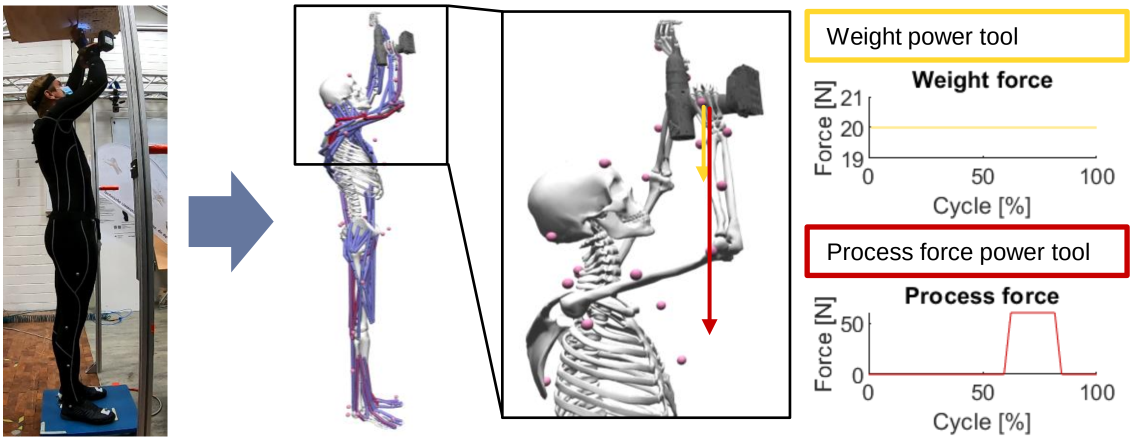

Figure 3. Simulation of the use case with a MHM by motion transfer and introduction of the forces of the power tool as external forces.

In order to evaluate the simulation of the *baseline scenario*, the simulation results were compared with measured data. For this purpose, muscle activation curves of muscles in the right arm and the trunk were compared with sEMG data of these muscle groups. Both consider the percentage of muscle activation based on the maximum activation of the muscle. Figure 4 shows a selection of the considered muscles for the exemplary cycle of the recorded movement.

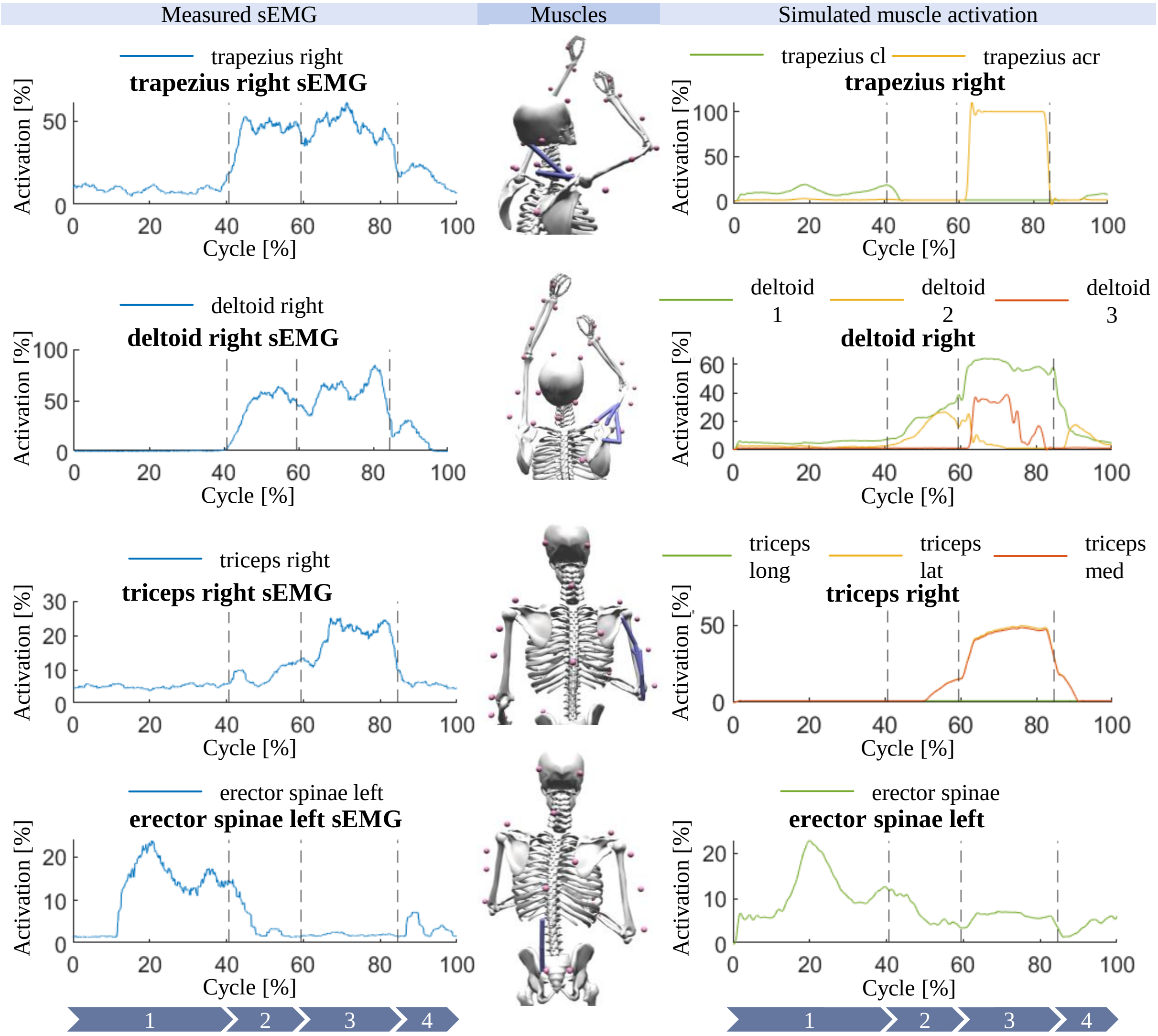

Figure 4. Comparison of the course of muscle activation for selected muscles with measured sEMG data during the motion (depicted in Figure 2)

The measured activation of the respective muscle group is shown on the left side, while the curves of the corresponding muscles in the human model are shown on the right side. The dashed lines separate the four steps of the working task. During the screwing process, the process force of the power tool is applied. It is shown that the curves of the simulated muscle activations are comparable to the measured muscle activations. Muscles that show little activation in the sEMG during the first step of the movement cycle also show this in the simulation. Most of the muscles of the right arm, shoulder and neck (exemplified by the musculus trapezius right, musculus deltoid right and musculus triceps right) show an increasing activation due to lifting of the arm (step 2) and especially during the screwing process (step 3). The muscle musculus erector spinae, on the other hand, tends to stabilize the upper body during the movements before lifting the arm (step 1), as the measured and simulated muscle activation shows.

2.3. Identification of use-case specific support concepts

When looking at the activation curves (see Figure 4), it can be seen that the muscle activation in the arm and shoulder area increases when the arm is lifted, especially when the process force of the power tool additionally acts on the right hand. In order to better support the user in these situations and thus reduce high muscle activations, various support concepts for the upper body were integrated into the human model as external forces in a simplified form in the following and their effect on the body was then assessed. An overview of the different support concepts for the user shows Figure 5. The reaction forces, which are generated due to the support on the arm, were modelled in a simplified manner as a force in the negative y direction into the centre of mass of the pelvis of the MHM. In addition to the reaction force, an external force of 50 N was also applied at the same position, which represents the weight of a body-worn support system.

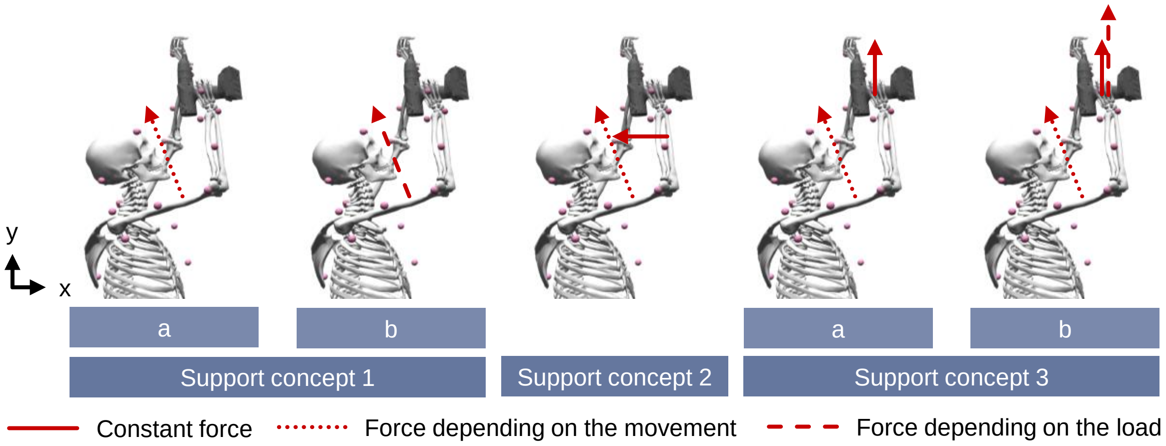

Figure 5. Various support concepts for the user when working at and above head height simplified as external forces supporting the MHM

2.3.1. Support concept 1

The *concept 1a* and *1b* only provide support forces to the upper arm to reduce the stress on the upper arm and the shoulder. The *concept 1a* addresses the generic motion of shoulder elevation and the *concept 1b* is specified for the use case with power tool. The force profile of *concept 1a* is a function of the shoulder elevation, while the profile of *1b* is derived from the shoulder joint moment with the load caused by the weight and the process force of power tool. Both profiles are calculated for forces applied to the lower third of the upper arm with an optimal force direction, which is perpendicular to the humerus. Consequently, the force for the simulation is divided into x and y direction of the world-coordinate depending on the shoulder angle. A possible force effect in the z direction, which could arise due to shear forces, is not considered here.

2.3.2. Support concept 2

Concept 2 is an extension of *concept 1a* by adding a support force to compensate the load on the lower arm caused by the weight of the power tool. This additional force is implemented in the simulation by a constant force of 20 N, applied to the lower third of the ulna. Here, as well, the force is distributed in x and y direction of the world-coordinate depending on the movement so that the force always acts perpendicular to the ulna. Similar to *concept 1,* potential forces in the z direction are also neglected.

2.3.3. Support concept 3

Concept 3a and *3b* are two other extensions to the *concept 1a*. Instead of a support force, which applied to the lower arm, they add forces directly to the power tool. *Concept 3a* aims for a weight compensation of the power tool and *concept 3b* focuses on the counteraction of the process force from the power tool.

Also in the simulation, the *concept 1a* is the basis for the *concepts 3a* and *3b*. However, since the power tool itself is not modelled in the simulation, but is only introduced into the MHM as an external force at the hand, direct support of the power tool cannot be modelled. Therefore, the support forces of the *concepts 3a* and *3b*, as well as the process forces of the power tool, are introduced as an external force at the metacarpus. For *concept 3a*, a constant force of 20 N is used in the positive y direction of the world-coordinate, which completely counteracts the weight of the power tool. Based on *concept 3a*, *concept 3b* adds a second support force (30 N) to the hand, which corresponds to half the process force (60 N) of the power tool and is only applied simultaneously with it. These concepts also neglect forces potentially occurring in the z direction.

2.4. Biomechanical evaluation of the support concepts

To compare the effects of the presented support concepts on the human body, they were implemented into the MHM-based biomechanical simulation. Figure 6 shows their effects on the activation of selected muscles in the right arm and trunk during the task. The black line represents the curve of muscular activation for the *baseline scenario* without support.

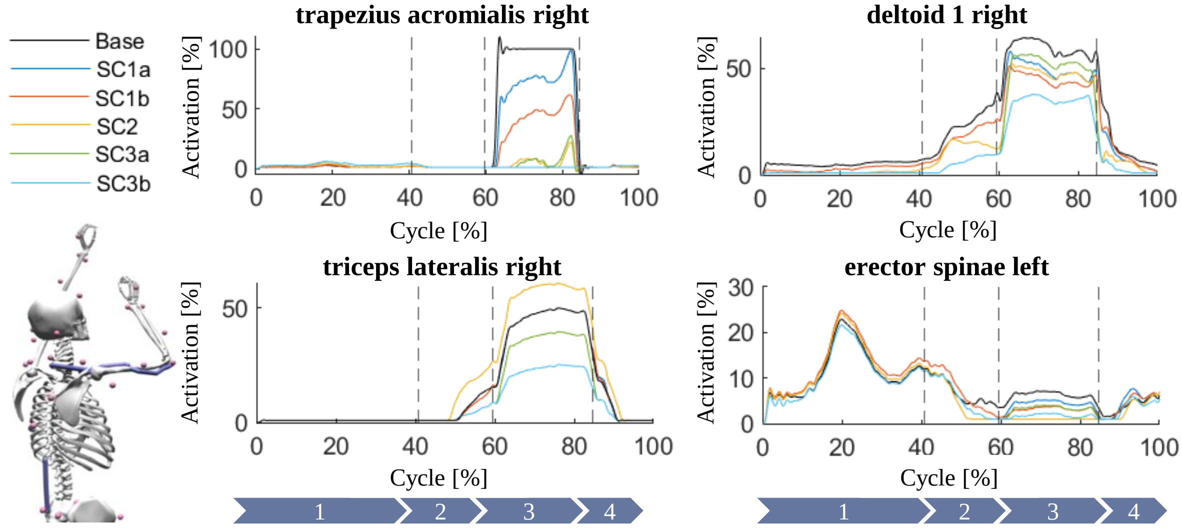

Figure 6. Muscle activation curves of selected muscles in dependence on the different support concept (Base = without support, SC = support concept as depicted in Figure 5)

It is shown that the activation of individual muscles responds differently to the various support concepts. In the following, the courses of the parts of the muscle groups musculus trapezius right (***trapezius acromialis right***), musculus deltoid right (***deltoid 1 right***) and musculus triceps right (***triceps lateralis right***) and the muscle musculus erector spinae left (***erector spinae left***) are considered. The muscles ***trapezius acromialis right***, ***deltoid 1 right*** and ***triceps lateralis right***, show almost no activity in the grasping-phase. These muscles are mainly activated when lifting the arm and screwing. For muscle ***trapezius acromialis right*** and muscle ***deltoid 1 right***, all concepts reduce their activation during the arm-lifting phase and screw-in phase. While the activation of muscle ***trapezius acromialis right*** can be significantly reduced, especially for *support concept 3b*, the range of reduction of muscle activation is lower for muscle ***deltoid 1 right***. However, here, *concept 3b* shows the greatest reduction in muscle activation as well. For both muscles, it is also evident that the *support concept 1b* reduces muscle activation more than *support concept 1a*. For muscle ***triceps lateralis right***, the response to the different support concepts varies. While *support concept 1a* and *1b* have no influence on activation, an underarm support force (*support concept 2*) actually increases activation of this muscle. For this muscle, however, *concept 3b* also shows high reduction of the muscle activation. For the muscle ***erector spinae left***, all concepts reduce the activation, but on a small scale because this muscle is less activated when the arm is lifted and screwed in, even during the basic movement. However, for this muscle, it shows that the support forces of most concepts increase activation in the period before and after lifting the arm and screwing (step 1 and step 4).

In addition to muscle activation, joint reaction forces can also be used to evaluate support concepts. In Figure 7, the reaction forces between the shoulder and humerus are considered as an example. Here, the forces in the global x and y direction are analyzed. For all joint reaction forces, it has been shown that the use case itself has the greatest influence on the load. As shown in Figure 7, the support concepts only have an influence on the joint reaction forces when lifting the arm and screwing, but this is small compared to the loads that arise due to the use case. However, the joint reaction forces in the shoulder are lower for all support concepts than the *baseline scenario* in the screwing process.

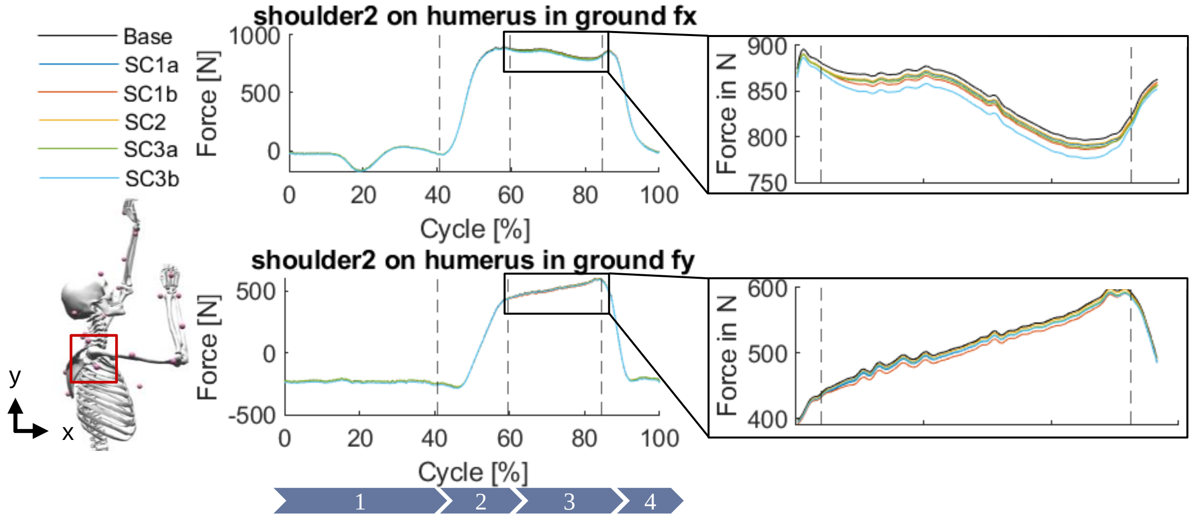

Figure 7. Joint reaction forces in the right shoulder in dependence on the different support concept (Base = without support, SC = support concept as depicted in Figure 5)

2.5. Further design elaboration

Based on the biomechanical analysis, the further design process for the identified support concept can now be carried out. The simplified support concepts will be translated into concrete designs of exoskeletons and then evaluated by means of further simulations and user tests.

3. Discussion

The presented approach shows a high potential for the evaluation of support concepts of exoskeletons in the pre-design phase of the product development process. By implementing this approach for the use case working at and above head height, the selected use case was first simulated with a MHM as *baseline scenario* and compared with experimental data. The *baseline scenario* was used to derive and evaluate possible support concepts. It was shown that the simulated muscle activations mapped the measured muscle activations well. Consequently, the simulation enables a good virtual representation of the load on the human musculature in the chosen use case.

Afterwards, the support concepts were simulated with the MHM and their effect on the human body was evaluated by looking at muscle activation and joint reaction forces. It can be seen that the potential for supporting the arm and shoulder lies particularly in the arm lifting and screwing phases. Although the joint reaction forces in the shoulder seem to be very dependent on the movement per se, a small reduction can be observed in this area due to the support. In addition, in this section, the defined support concepts show a reduction in activation for almost all considered muscles. Only *support concept 2* evokes a higher activation for muscle ***triceps lateralis right***. Furthermore, it is visible that the application of a force that is matched to the loading situation (*support concept 1b*) reduces muscle activation more than support that is only based on the movement (*support concept 1a*). Consequently, it could make sense to provide support through an exoskeleton not only depending on the movement of the user, but also on the current load situation. Furthermore, by reducing the process force of the power tool, the *support concept 3b* seems to have very high potential for reducing muscle activation in this use case. Consideration of a possible coupling between an exoskeleton and a power tool to support the user by reducing the process forces occurring during the use case could be useful and should be part of further considerations.

For the presented approach, support concepts are used because, due to their abstraction as external forces, no concrete design elaborations are necessary. This enables the use of the approach in very early phases of product development. However, in this way the support situation was also represented in a simplified way. By introducing the reaction force of the support as an external force directed in negative y direction to the pelvis, an optimal force conduction of the reaction force in the exoskeleton is assumed. Also moments, which arise due to the support and are partly absorbed by the exoskeleton or can be introduced to the body, are not considered here. In addition, the motion in the human model was not adapted to the different support concepts. Consequently, it is assumed that the support force has no influence on the movement of the human. Furthermore, all concepts assume support in global y or global x and y direction. Thus, shear forces that could occur due to the support in z direction are left out for the simulation. Lastly, this approach cannot provide information on whether the support concept is providing too strong relief to the user. If the user's relief is too strong, this could result in loss of muscle strength (Gao *et al.*, 2018).

4. Conclusion

The present contribution shows an approach for evaluating support concepts of exoskeletons for selected use cases using a musculoskeletal human model. We have defined support concepts in which possible support forces are mapped as external forces without need to make concrete designs. This makes this approach suitable for application in the early phases of product development. Due to using a musculoskeletal human model, the influence of the support concepts on the user can be evaluated based on biomechanical criteria such as muscle activations and joint reaction forces. This enables initial proactive evaluations without prototyping in conjunction with empirical user studies, which can save time and money. For promising support concepts, design concepts can subsequently be developed and these can be evaluated and optimized through further simulations and user tests.

We have implemented the approach for the use case working at and above head height using a power tool. By comparison of the simulated to the empirically measured muscle activations, it could be shown that the simulation, which represents the baseline scenario, matches the measurements quite well. Consequently, five different support concepts were defined, which add support only at the upper arm, additionally at the forearm or additionally at the hand. With the help of the musculoskeletal simulation, the effects of these support concepts on the human body could be estimated and the potential of the individual support concepts could be evaluated. Despite the limitations, the approach offers the possibility of a well-founded evaluation of individual support concepts in the early phases of product development and thus the basis for the further elaboration of promising support concepts.

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