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Simulation Framework for Active Upper Limb Exoskeleton Design Optimization Based on Musculoskeletal Modeling

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Abstract

This paper presents an approach for analyzing the biomechanical exoskeleton-human interaction with the aim to optimize the technical design of an active upper limb exoskeleton based on musculoskeletal modeling and simulation.
Preliminary results of an artificially generated movement of a human musculoskeletal model (AnyBody™) promise significant potential for a quantitative analysis approach using musculoskeletal modeling. Varying the implemented gravity compensating factor indicates potential of adjusting partial muscle relief and inner reaction forces and moments using an active upper limb exoskeleton. The analysis points out that, compared to muscle activations, inner human reaction forces and moments request different control parameter configurations for an assumed optimal assistance.

Kurzzusammenfassung

Simulationsumgebung zur Optimierung aktiver Oberkörper-Exoskelette basierend auf muskuloskelettaler Modellierung

In dieser Veröffentlichung wird ein Konzept zur Analyse der biomechanischen Exoskelett-Mensch-Interaktion mit dem Ziel der simulationsbasierten Optimierung von aktiven Oberkörper-Exoskeletten, basierend auf Muskel-Skelett-Modellierung mit dem AnyBody™ Modeling System, vorgestellt. Erste Simulationsergebnisse einer Hebebewegung prognostizieren vielversprechende Möglichkeiten der quantitativen biomechanischen Analyse solcher aktiver Exoskelett-Mensch-Systeme. Die vorgestellten Simulationsergebnisse des Exoskelett-Mensch-Modells zeigen die Komplexität des Zusammenhangs zwischen optimierter Einstellung von Steuerungsparametern wie beispielsweise der implementierten Gravitationskompensation und den biomechanischen Belastungsparametern im Schulter-Arm-Komplex auf. Es zeigt sich bei der Analyse der Gravitationskompensation, dass sich – im Vergleich zu den Muskelaktivitäten – die angenommene optimale Entlastung für innere Körperreaktionskräfte und –momente hinsichtlich der einzustellenden Gravitationskompensation unterscheidet.

Keywords
Digital human modeling, simulation-based optimization, musculoskeletal modeling, active upper limb exoskeleton, exoskeleton control

1 Introduction and Motivation

Demographic change forces employers to provide more technical assistance systems to their staff to relieve the burden on the musculoskeletal system and enable a longer, healthier and safer working life. Investigations of [Noe16] complain about 21.6 billion Euro loss of gross value due to incapacity to work days caused by musculoskeletal disorders. Prognoses predict [Kar17] a worldwide market volume of up to 5.6 billion dollars in 2025 for the exoskeleton industry, where especially work-assisting devices will grow exponentially. Active upper limb exoskeletons could play a key role for possible future solutions for specific work tasks like lifting heavy parts and working overhead. A bottleneck of the exoskeleton industry for breaking through the big application market is the analysis and evaluation of exonerative effects on the musculoskeletal system. Ergonomists and developers need assistance to optimize and validate their application and person-specific exoskeletons for the applied movements and loads.

Among the digital human modeling approaches, human-technology interaction attracts increasing attention because technology such as exoskeletons affect the inner loads on the musculoskeletal system as well as the interface loads between the human and the exoskeleton. End-users of exoskeletons vary in anthropometry, muscle strength, body mass and manner of executing movements, and each application scenario differs concerning movement and load-specific boundary conditions. Digital human models comprising the human as well as the exoskeleton in a single mechanical system offer engineers the possibility to consider all of these aspects in parallel.

In the studies of [Zho15] passive kinetic elements were being analyzed and optimized using digital musculoskeletal modeling. [Sho16] investigated in a parametric study the effect of assistive torque concerning metabolic energy consumption in a box-lifting task for a musculoskeletal model as well.

The aim of the study in this paper is to analyze the effect of the specific upper limb exoskeleton on the shoulder-arm complex of a musculoskeletal model. As biomechanical parameters muscle activations and inner reaction forces and moments will be considered. The active exoskeleton will be investigated concerning adjustable control parameters like the gravity-compensating factor in varying load cases. Based on these investigations, an enhanced comprehension of the adaptive active exoskeletons will be achieved.

2 Active Upper-Limb Exoskeleton Stuttgart Exo-Jacket

In comparison to passive assistive devices active upper limb exoskeletons have enhanced possibilities for different applications based on adaptive software control [Gop16].

The Stuttgart Exo-Jacket is such an active and modular exoskeleton platform for developing and demonstrating technical components for active electromechanical wearable devices. Version 2 of the Stuttgart Exo-Jacket is applicable as a carrying and lifting device for heavy objects in industrial work scenarios. Version 2 has 18 degrees of freedom including four active joints for elbow flexion/extension and glenohumeral flexion/extension assisting right and left upper extremities. Elevation of sternoclavicular joints is passively supported through a force-generating gas spring. Both shoulder mechanisms additionally include a third and fourth gas spring to prevent mechanical misalignment for the wearer´s shoulder complex. The fifth and sixth gas spring generate reaction forces in ventral direction for the shoulder mechanism to relieve interaction forces in the upper arm bracings of the exoskeleton.

In Table 1, the ergonomic range of motion for the Stuttgart Exo-Jacket II is prescribed to limit it with regard to suitable application scenarios.

Table 1: Ergonomic range of motion for Stuttgart Exo-Jacket II

Wrist Flexion	-15°…15°
Wrist Abduction	-10°…10°
Elbow Flexion	0°…150°
Elbow Pronation	0°…160°
Glenohumeral Flexion	0°…90°
Glenohumeral Abduction	0°…10°
Glenohumeral External Rotation	-45°…25°
Sternoclavicular Elevation	0°…30°
Sternoclavicular Protraction	-10°…20°
Sternoclavicular External Rotation	-5°…5°
Pelvis-Thorax Flexion	-10°…10°
Pelvis-Thorax External Rotation	-20°…20°
Pelvis-Thorax Lateral Bending	-15°…15°

With some limitations (Table 1) the active upper limb exoskeleton can be applied in overhead work scenarios as well (Fig. 1).

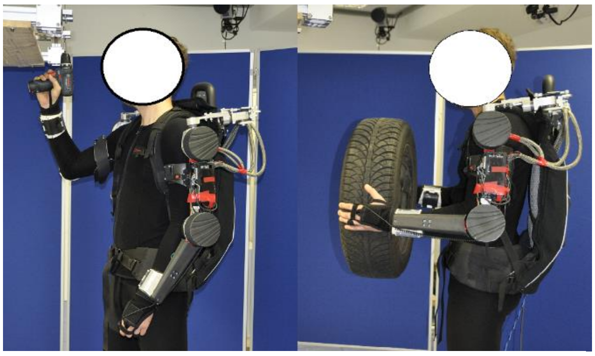

Figure 1: Stuttgart Exo-Jacket II in overhead and carrying work scenarios

The concept of the Stuttgart Exo-Jacket focuses on modularity which implies an optional addition of a passive leg module in case of high-load applications to transfer the load from the hip to the ground to relieve the wearer´s legs as well [Ebr17].

3 Modeling of Human-Exoskeleton System

A human-exoskeleton system works cooperatively together with the human musculoskeletal apparatus. The interaction between the exoskeleton and the human body determines whether or how the exoskeleton can assist the desired movements. A central issue in the modeling work is thus to simulate the response of the human body subject to external forces and torques exerted by the exoskeleton.

The human-exoskeleton system in this work comprises two modules:

(i) A musculoskeletal human body and (ii) an exoskeleton model. The musculoskeletal model comprises all the significant bones, joints and muscle elements of the human body. The exoskeleton model contains all segments, joints, passive elastic elements and motors of the exoskeleton. The two parts are connected and form a single mechanical system in the analysis model.

3.1 Musculoskeletal Model

For the analysis approach presented in this paper, the musculoskeletal modeling and simulation tool AnyBody (AnyBody Modeling System (AMS) in Version 7.2) is used as biomechanical analysis tool. AMS in general is capable of analyzing rigid multi-body systems like the musculoskeletal system of the human or other creatures. In addition, AMS is capable of including external objects, loads and motion specifications to compute inner body torques and forces through an inverse dynamic approach. Having motions and external forces as measured input, AMS formulates the dynamic equilibrium equations. These equations are typically redundant because the system contains more actuators than degrees-of-freedom. Therefore, the equations are solved as an optimization problem to compute the muscle and joint forces [Ras01]:

$$\underset{f}{\text{Minimize}} \quad G\left(f^{(M)}\right) \tag{1}$$

$$\textit{subject to} \quad Cf = r$$

$$\textit{and} \;\; f_i^{(M)} \geq 0, \quad i \in \left\{1, \dots, n^{(M)}\right\} \tag{2}$$

G defines the objective function of the recruitment process stated in terms of muscle forces, $f^{(M)}$, and minimized with respect to all unknown forces (muscle forces and joint reactions) in the problem. C is the coefficient matrix and r contains all known applied loads, inertia, coriolis, gyroscopic and centripetal forces. Equation (2) is a non-negativity constraint on the muscle forces to signify that muscles can only pull and not push [Ras01].

The human model in AMS for this analysis is built on the top-down principle based on the squatting human model from the AnyBody Managed Modeling Repository (50th percentile of European male). The model has contact to the floor through a ground predictive force plate [Ska17]. 25 predictive ground reaction force elements on each feet of the human model generate ground reaction forces and are included in the muscle recruitment process.

An additional kinematic driver keeps the center of mass above the feet-floor contact point. The driver moves the center of mass of the human model in x- and y-direction to keep it standing upright in a balanced posture. In the left and right hand, the model is being pulled down by two external forces, representative as holding two dumbbells.

3.2 Exoskeleton Model

To generate the digital exoskeleton model, the exoskeleton is first designed in CAD using SolidWorks and added to AMS using the AnyBody Exporter for SOLIDWORKS® plugin.

The two main technical core elements of the exoskeleton are the passive shoulder mechanism and the actively controlled gravity compensation for torque assistance of human glenohumeral joint and elbow, flexion and extension movements. The implemented shoulder mechanism of the investigated exoskeleton model includes six DOFs, one active motor element and three additional kinetic elements for both sides (S_1, S_2, S_3) which passively hold the arm exoskeleton structure and direct the load from the wearer´s lower arm to the back plate to offload the human´s shoulder complex. Passive gas spring elements are defined as constant unidirectional forces to minimize glenohumeral inner reaction forces, therefore, springs S_1 and S_2 push with 100N and 150N. S_2 prevents misalignment for the glenohumeral axis and axis of the shoulder motors. The back plate is firmly connected to the wearer´s hip. Additionally, two spring elements model the connection between the back plate and the thorax segment of the human model.

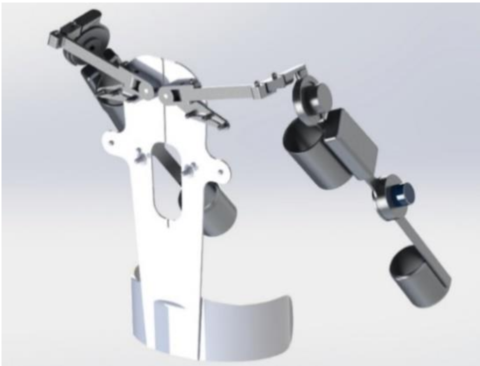

Figure 2: CAD-model of exoskeleton

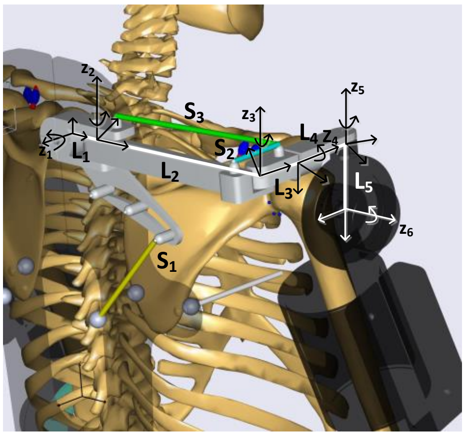

Figure 3: Shoulder mechanism of the Stuttgart Exo-Jacket II

As control functionality for the four motor elements (glenohumeral flexion-extension and

elbow flexion-extension), an open loop gravity compensation, neglecting abduction and elevation of human shoulder complex, is implemented for the exoskeleton model. The real exoskeleton hardware contains an additional interaction control which compensates inertia and friction. For the musculoskeletal modeling approach, these control aspects are neglected.
Gravity compensation of the exoskeleton is computed as follows:

$$M_{Shoulder,Exo} = [m_{Upperarm,Exo} l_{1,1} \sin(\alpha) + m_{Lowerarm,Exo}\left(sin(\alpha) l_1 + \sin(\alpha+\beta)\, l_{2,2}\right)]g + (F_{Grav.,ext.} * D_{Grav.Comp.}) * (sin(\alpha) l_1 + \sin(\alpha+\beta)\, l_2) \quad (3)$$

$$M_{Elbow,Exo} = [m_{Lowerarm,Exo} l_{2,2} \sin(\alpha+\beta)]g + (F_{Grav.,ext.} * D_{Grav.Comp.}) * \sin(\alpha+\beta)\, l_2 \quad (4)$$

$M_{Shoulder,Exo}$ and $M_{Elbow,Exo}$ are motor torques dependent from presumed masses of the exoskeleton and human rigid segments, $m_{Upperarm,Exo}$, $m_{Lowerarm,Exo}$, human and exoskeleton lengths, l_1, $l_{1,1}$, l_2, $l_{2,2}$, and external gravity force, $F_{Grav.,ext.}$, multiplied with a gravity compensating factor, $D_{Grav.Comp.}$. The masses of the exoskeleton and human arm are taken from the AnyBody and SolidWorks model properties.

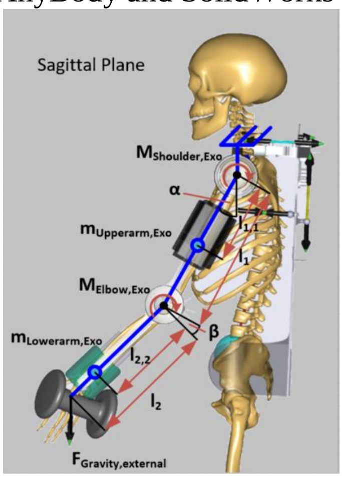

Figure 4: Exoskeleton-human model as inverted double pendulum

3.3 Implementation of Exoskeleton-Human System

To implement the exoskeleton-human model in AMS, the exoskeleton needs to be kinematically and kinetically connected to the musculoskeletal model.
Kinematically, the exoskeleton is connected to the musculoskeletal model through five contact points:

Table 2: Kinematic Contact Conditions

Right Radius to Right Lowerarm Bracing	6 contact elements (3 Rot., 3 Transl.)
Right Humerus to Right Upper Arm Bracing	6 contact elements (3 Rot., 3 Transl.)
Left Radius to Left Lowerarm Bracing	6 contact elements (3 Rot., 3 Transl.)
Left Humerus to Left Upper Arm Bracing	6 contact elements (3 Rot., 3 Transl.)
Pelvis to Exoskeleton Back Plate	6 contact elements (3 Rot., 3 Transl.)

Kinetic contact conditions between human and exoskeleton segments are adjustable and implemented to prioritize the force transmission contact areas between the exoskeleton and the human bones. The exoskeleton is in contact with the human model at the radius, humerus, thorax and pelvis segments through kinetic contact conditions. Unidirectional contact elements with a variable strength to generate high static friction forces are used in AMS. For this analysis, each contact muscle has a maximum strength of 10.000 N.
Table 3: Kinetic Contact Conditions

Right Radius to Right Lowerarm Bracing	12 contact elements (6 Rot., 6 Transl.)
Right Humerus to Right Upper Arm Bracing	12 contact elements (6 Rot., 6 Transl.)
Left Radius to	12 contact elements (6 Rot., 6 Transl.)

Left Lowerarm Bracing	
Left Humerus to Left Upper Arm Bracing	12 contact elements (6 Rot., 6 Transl.)
Pelvis to Exoskeleton Back Plate	12 contact elements (6 Rot., 6 Transl.)

The kinetic contact elements for upper arm, lower arm, thorax and pelvis are implemented in AMS and will be considered in the polynomial muscle recruitment process, in this case of order 3:

$$G\left(f^{(M)}\right) = \sum_{\mathrm{i}}^{N} \left(\frac{f_{muscle,i}}{N_i}\right)^3 \qquad (5)$$

The contact elements between the exoskeleton and the human segments are included in the muscle recruitment process of AMS, which solves an optimization problem including weighting of each contact element depending on its assumed strength. This offers an approximation approach for generated exonerative support effect by the exoskeleton for human musculoskeletal system.

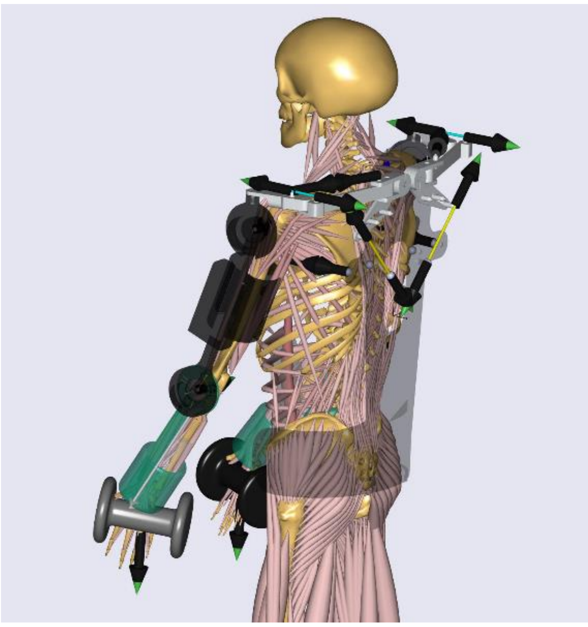

Figure 5: Exoskeleton-human model in AMS

4 Method and Simulation Setup

To evaluate the performance of the exoskeleton, a simplified representative scenario of lifting and carrying heavy objects is modeled. For preliminary simulation results the movement is artificially generated using kinematic drivers for human joints. These kinematic drivers keep the upper body straight. The human model holds two dumbbells during lift representing the weight of an external mass in each hand. The lifting motion ranges from hip to shoulder height which is contained in the ergonomic range of motion for the upper limb exoskeleton, the Stuttgart Exo-Jacket. The movements for human upper limbs execute constant velocities of elbow flexion (15°/sec), glenohumeral flexion (20°/sec), sternoclavicular elevation (3°/sec), sternoclavicular protraction (6°/sec) and sternoclavicular axial rotation (3°/sec) as a lift scenario of three seconds.

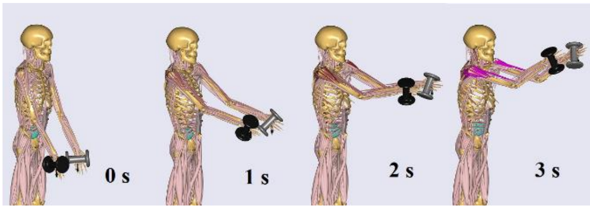

Figure 6: Lift scenario sequences

The lift scenario is analyzed without and with the exoskeleton in different external load and exoskeleton control variations.

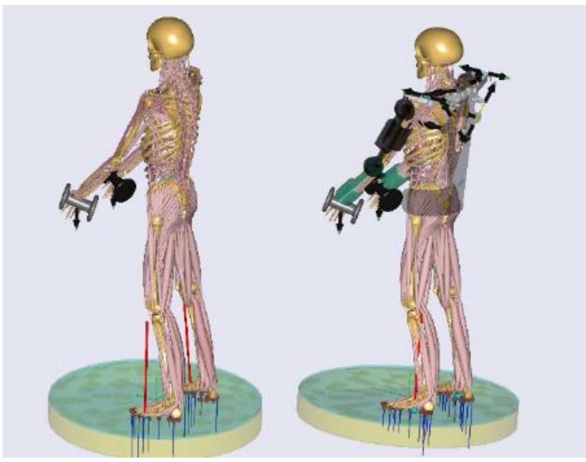

Figure 7: Musculoskeletal model without and with exoskeleton

5 Preliminary Analysis Results

In this section, preliminary results of the inverse dynamic studies are considered, including inner human body reaction forces and envelopes of muscle activities of the shoulder-arm complex without and with the exoskeleton in varying load and gravity-compensating configurations. The muscle activity is the fraction of each muscle´s maximum strength, taken to perform given dynamic. Envelopes for activities of muscle groups in AMS are enclosing all single muscle activation curves as an indicator for the activity of the whole muscle section.

The working hypothesis is to facilitate optimal assistance by dimensioning control parameters based on personalized musculoskeletal modeling. As indicators for approximation of optimal assistance the aforementioned biomechanical load parameters amongst others will be considered. The thick line of each plotted biomechanical load parameter indicates the assumed optimal assisted configuration of the exoskeleton.

5.1 Muscle Activations

Muscle activities are representatively taken as parameters to measure exonerative effects of the exoskeleton on the human musculoskeletal system. In this section of the study, muscle activities are considered for different load and control configuration parameters with and without exoskeleton.

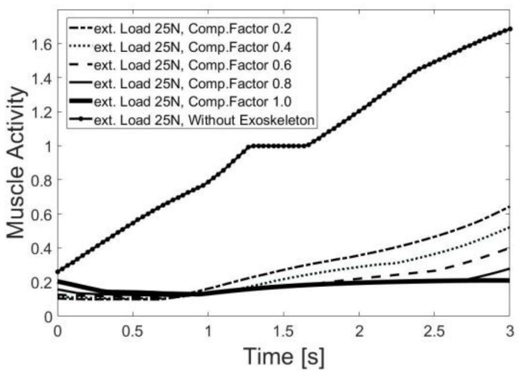

Figure 8: Envelopes of muscle activations for the left shoulder-arm complex

Figure 8 shows a reduction of simulated muscle activities in envelope curves of all muscle activities in the shoulder-arm complex. Beyond 1.5 seconds during lift scenario, the model is not capable anymore to execute the movement without the exoskeleton. To indicate fine adjustment optimization possibilities, five different gravity compensating configurations are plotted as well.

Figure 9 indicates a dependency between muscle activations of the shoulder-arm complex and the gravity compensating factor, the more support the more the muscles are relieved.

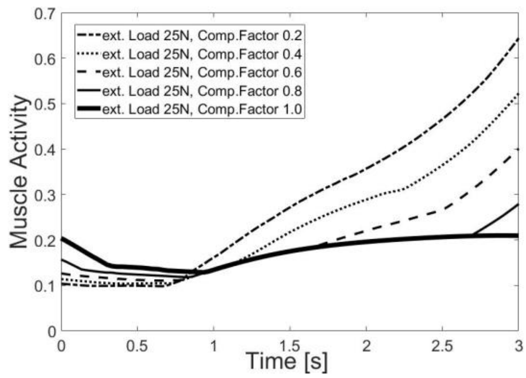

Figure 9: Envelopes of muscle activations for the left shoulder-arm complex with varying gravity comp. factor

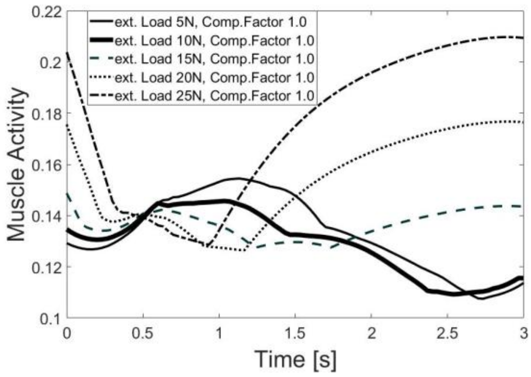

Figure 10: Envelopes of muscle activations for left shoulder-arm complex with varying external load

Figure 10 shows that in varying load scenarios muscle activations differ with the same gravity compensating factor, meaning that the exoskeleton partially compensates the external weight. For the straight arm posture at the end of the lifting movement, differences between load cases are more pronounced in muscle activations.

5.2 Inner Human Reaction Forces and Moments

Inner human reaction forces are indicators of human body loads caused by external loads or awkward postures, because the latter are often caused by vanishing moment arms or unavailable major muscles and joint moment production under those circumstances produce high joint reactions in addition to high muscle activities. In this section, for the described simulation setup, the shoulder-arm complex of the musculoskeletal model is investigated concerning compression forces in the glenohumeral joint and the reaction moments for elbow and glenohumeral flexion.

The simulation results show a marginal exonerative effect of the Exo-Jacket with regard to compression forces in the glenohumeral joint for full gravity compensation in the described lifting scenario. In comparison, elbow flexion and glenohumeral flexion moments indicate a more complex optimal adjustment of gravity compensation to minimize the considered load parameters.

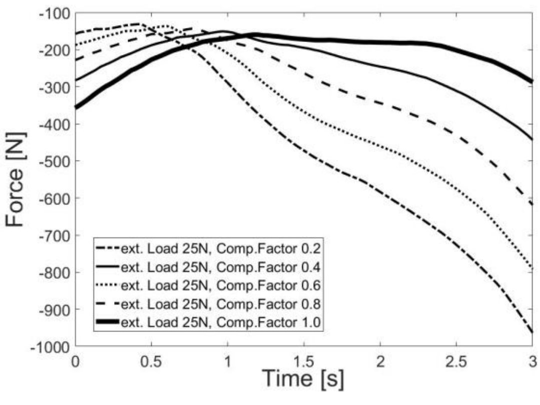

Figure 11: Compression forces in left glenohumeral joint with varying gravity comp. factor

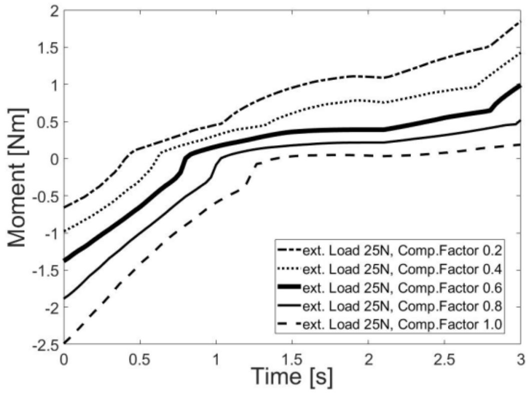

Figure 12: Flexion moment in left elbow joint with varying comp. factor

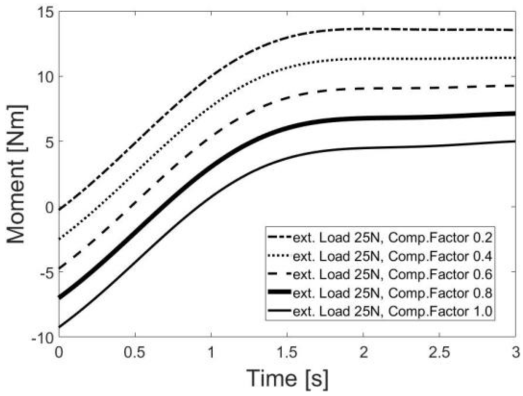

Figure 13: Flexion moment in left glenohumeral joint with varying comp. factor

The thick lines designate the optimal gravity compensating factor for minimal flexion moments in the simulated load scenarios. The most gravity-compensating configuration does not seem to be the most relieving, regarding inner reaction forces and moments in glenohumeral and elbow joint.

6 Discussion and Future Work

In this study, an artificially generated lift movement in different load and control parameter configurations has been analyzed. Dependencies between partial gravity compensation and muscle activations could be pointed out. Inner human reaction forces and moments indicate a more complex dependency. Parameter studies will shed more light on dependencies between technical control parameters, external load and movement of the exoskeleton-human model.

Future work will also include real motion data to generate more realistic movements. Additionally, external force measurements will be taken into account. Representative application scenarios will be industrial carrying and lifting heavy load and overhead working postures. Out of these more realistic movements, a more sophisticated analysis of considered biomechanical load scenarios can be developed.

As validation approach comparison of simulated and real measured muscle activations using sEMG (surface electromyography) data will be considered in future work of the author. Validation of modeled inner human reaction forces and moments is a further challenge to be dealt with.

The final goal of this work is the individualized adaptable design of active upper limb exoskeletons, based on realistic mounting scenarios using a real hardware exoskeleton based on the Stuttgart Exo-Jacket development platform. It will be adaptable to the specific application, person and load.

7 Acknowledgements

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