DHM supported assessment of the effects of using an exoskeleton during work

Francisco Garcia Rivera*, Dan Högberg, Maurice Lamb and Estela Perez Luque

School of Engineering Sciences,
University of Skövde,
Högskolevägen, 541-28 Skövde, Sweden
Email: francisco.garcia.rivera@his.se
Email: dan.hogberg@his.se
Email: maurice.lamb@his.se
Email: estela.perez.luque@his.se
*Corresponding author

Abstract: Recently, exoskeletons have been gaining popularity in many industries, primarily for supporting manual assembly tasks. Due to the relative novelty of exoskeleton technologies, knowledge about the consequences of using these devices at workstations is still developing. Digital human modelling (DHM) and ergonomic evaluation tools may be of particular use in this context. However, there are no standard integrations of DHM and ergonomic assessment tools for assessing exoskeletons. This paper proposes a general method for evaluating the ergonomic effects of introducing an exoskeleton in a production context using DHM simulation tools combined with a modified existing ergonomic assessment framework. More specifically, we propose adapting the Assembly Specific Force Atlas tool to evaluate exoskeletons by increasing the risk level threshold proportionally to the amount of torque that the exoskeleton reduces in the glenohumeral joint. We illustrate this adaptation in a DHM tool. We believe the proposed methodology and the corresponding workflow can be helpful for decision-makers and stakeholders when considering implementing exoskeletons in a production environment.

Keywords: digital human modelling; DHM; assessment; ergonomics; exoskeleton; Assembly Specific Force Atlas; ASFA.

Reference to this paper should be made as follows: Rivera, F.G., Högberg, D., Lamb, M. and Luque, E.P. (2022) 'DHM supported assessment of the effects of using an exoskeleton during work', *Int. J. Human Factors Modelling and Simulation*, Vol. 7, Nos. 3/4, pp.231–246.

Biographical notes: Francisco Garcia Rivera is a PhD candidate at the University of Skövde. His research interests involve human factors in the industry and applying new technologies such as virtual reality or augmented reality to the design process.

Dan Högberg is the Leader of the User-Centred Product Design (UCPD) Research Group at the University of Skövde. His research is about making user-centred information, e.g., ergonomics knowledge, relevant and easily available to product designers and engineers.

Maurice Lamb is a Senior Lecturer at the University of Skövde. Maurice is an interdisciplinary researcher with a background in cognitive science, philosophy, engineering, and computer science. His primary research interests lay in applying complex dynamical systems methods to solving challenges in human-robot and human-agent interaction contexts.

Estela Perez Luque is a PhD candidate at the University of Skövde. Her research interests involve drivers' ergonomics and human motion prediction to improve the predictions of human behaviour in DHM tools when analysing vehicle ergonomics.

This paper is a revised and expanded version of a paper entitled 'A framework to model the use of exoskeletons in DHM tools' presented at AHFE, New York, 25–29 July 2021.

1 Introduction

Simulation has become a key tool across many industries for providing insights into the potential impacts of certain design alternatives of anticipated systems or changes to existing systems, enabling stakeholders to make data-based decisions. In the context of production design, simulation tools have become an integral part of the design and decision processes by allowing for rapid testing of multiple workstation configurations without interrupting production (Rüßmann et al., 2015; Schluse et al., 2018). Digital human modelling (DHM) tools are part of a suite of simulation tools and methods designed to add digital humans with diverse anthropometries (Brolin et al., 2019) into computer-aided design (CAD) and simulations (Scataglini and Paul, 2019; Demirel et al., 2021). In DHM simulations, the manikin can be simulated as completing various production tasks, including interacting with production tools and equipment. For any given manikin in a DHM simulation, DHM tools can provide predictions about various ergonomic factors relating to using a candidate workstation with some set of tools. This paper will explore one potential method for using DHM tools to evaluate the ergonomic impact of introducing an exoskeleton in a production context. To this end, we will discuss critical considerations for simulating exoskeletons in DHM tools and provide an example of one such simulation along with a demonstration of simulation results as they relate to a widely used ergonomic assessment tool. Given the relative lack of independent methods for evaluating exoskeletons in varied production environments and with varied users, we believe further research relating to evaluations of exoskeletons in DHM tools is critical. However, given the current state of the art, we will only provide a rough sketch of one approach to exoskeleton evaluation using a DHM tool.

One of the core objectives of DHM tools is to support the ergonomic evaluation of workstations with the outcome that workstations will provide good working conditions for workers. However, there are some situations in which a workstation cannot be designed or redesigned to provide ideal ergonomics (this is a common situation in industries such as automotive or construction), increasing strain on workers and risks of injury. In some of these situations, exoskeletons may provide a good solution, balancing cost or product constraints and the ergonomic needs of the worker, as well as compliance with applicable regulations in regards to ergonomics.

Upper-body exoskeletons that support overhead work seem to be a promising solution to this kind of challenge, potentially requiring little to no modification of the workspace while providing potentially significant ergonomic improvements for workers (Tröster et al., 2018; Bornmann et al., 2020; Maurice et al., 2020). Unfortunately, due to the relative novelty of commercial exoskeleton technologies, few independent studies identify the ergonomic consequences of using exoskeletons at workstations and almost no insight into long-term usage impacts. DHM tools may be of particular use in this context, providing insights into the ergonomic impacts of exoskeletons and providing the possibility for simulated comparisons among specific exoskeleton options for a specific use case and across a diverse group of potential workers.

Existing research on the effects of wearing exoskeletons typically focuses on muscle activation using electromyography (EMG) sensors and joint angle/torque measurements based on motion capture (mocap) in either lab or production environments. Regardless of the context, these studies typically compare the differences in muscular activity or range of motion between wearing an exoskeleton and not wearing it. Studies on how exoskeletons influence muscular activity usually find a reduction in the muscular activity in the shoulder muscles when wearing exoskeleton (Kiguchi and Hayashi, 2012; Huysamen et al., 2018; de Vries et al., 2019; Schmalz et al., 2019) When EMG is not involved, range of motion tends to be the focus. For example, Baltrusch et al. (2018) and Perez Luque et al. (2020) investigated how exoskeletons influence workers' range of motion. There are fewer studies published that explore the ergonomic impacts of exoskeletons using simulations in DHM tools. However, examples include Zhou (2020), who presented a simulation framework for designing and evaluating exoskeletons, and Fritzsche et al. (2021), where they used the DHM tool AnyBody to do biomechanical simulations of how exoskeletons influence physical strain. Similar to studies in the field, DHM-based exoskeleton studies typically focus on specific human anthropometries and/or exoskeleton systems (Tröster et al., 2018). The insights from the simulations are limited to specific exoskeletons and users, and there is little discussion of methods for comparisons across systems or use contexts. Thus, while these studies provide valuable data points, it is difficult for stakeholders to base decisions on these studies or compare their situations and simulations to these studies.

Several commonly used physical ergonomics evaluation tools are used to assess work-related musculoskeletal disorders risks across production contexts. Typically, these tools focus their assessments on specific bodily exposures, such as postures or forces applied during work generally. Moreover, ergonomics evaluation tools are typically used to assess certain types of work activities. Examples of tools are *Rapid Upper Limb Assessment* (*RULA*) for assessing loads on upper limbs (McAtamney and Corlett, 1993), *Rapid Entire Body Assessment* (*REBA*) (Hignett and McAtamney, 2000) and *Ovako Working Posture Analysing System* (*OWAS*) (Karhu et al., 1977) for assessing full bodywork. Because one main objective of exoskeletons is to provide force support during work, e.g., offering force support on upper arms during overhead work, assessment tools that consider lifting tasks and forces can potentially be applicable to assess the effect of using exoskeletons during work. Examples of such assessment tools are *National Institute for Occupational Safety and Health* (*NIOSH*) *Lifting Equation* for assessing lifting tasks (Waters et al., 1993) and *3D Static Strength Prediction Program™* (*3D SSPP*) for assessing static strength and estimating the percentage of the population capable of exerting force demands.

Often ergonomic assessment tools, as initially developed, depend in part on expert human observers in specific or well-defined scenarios. For tools like the 3D SSPP, force estimations can be further complicated by the complexities involved in estimating force capabilities via biomechanics modelling (Hall et al., 2021).

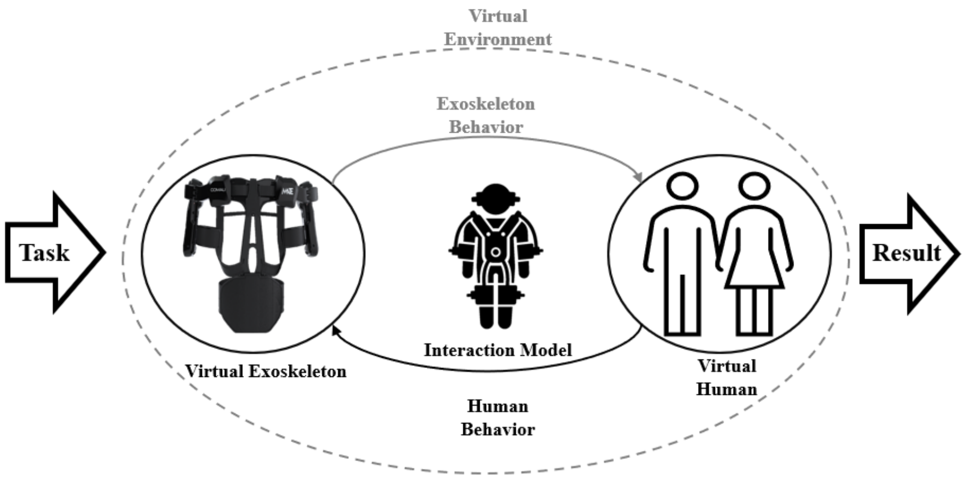
Some ergonomic assessment tools have been adapted in the context of DHM tools, allowing for automatic and fast insights. Not all of these tools may be useful or meaningful in the context of exoskeleton evaluation and comparison, and there is a general lack of standard criteria and methods for assessing the effects of exoskeletons using these tools (Gull et al., 2020).

When considering which assessments might be helpful for exoskeleton evaluation, it is essential to consider the granularity and type of information needed. Some tools provide easy to read and interpret total risk scores or colour schemes to signify risk levels, as in the RULA, REBA, or OWAS tools. However, these results may not relate to relevant features of the workstation, exoskeleton, or production processes, such as forces or torques applied to the worker's end-effectors or joints. While it may be helpful to have a high-level go/no go insight into the impact of an exoskeleton, more granular insight might clarify which changes to the workstation can complement a given exoskeleton. Specific assessment tools may even allow for more direct and granular comparisons between exoskeletons in specific contexts.

While no single assessment tool fulfils all the ergonomic evaluation needs in the current context, one potentially important, and so far unexplored, candidate method for comparative and quantitative evaluation of exoskeletons is the *Assembly Specific Force Atlas* (*ASFA*) evaluation tool (Schaub et al., 2015). ASFA is based on an empirical collection of hand force capabilities of 273 male workers, measured in six specific force directions and in nine specific vertical distances from ground level to load. The tool estimates a maximum hand force based on an expected maximum voluntary contraction based on the empirical data. Maximum hand force estimates are specified in terms of population percentile, posture, force direction, and several other pre-defined factors. Factors are used to adjust the estimated maximum force by considering aspects such as age, gender, frequency, symmetry/asymmetry, one/two-handed force exertion, and duration. When designing a workstation, the 15th percentile value, i.e., assuming that 85% of the population would be able to exert the force safely, is recommended as a starting point to ensure a sufficient safety margin. When assessing a potential workstation, a force index can be calculated by dividing the actual (or simulated) forces involved in a workstation by the maximum safe force (estimated based on selected percentile and factors). This force index serves as the basis for identifying a simplified colour coded risk level indicator. A simplified version of ASFA is implemented as part of the holistic ergonomics assessment tool Ergonomic Assessment Worksheet (EAWS) (Schaub et al., 2012).

In this work, we build on our previous study in which we proposed a framework to simulate the effect of exoskeletons in DHM tools (Rivera et al., 2021) (Figure 1). More specifically, we propose the adaptation of the ASFA tool to the evaluation of exoskeletons, and we use the previously proposed framework to illustrate how to adapt the ASFA for evaluating exoskeletons in DHM tools. The particular application in this paper is intended to be illustrative of the proposed method and not a rigorous claim about a particular exoskeleton's impact. Thus, this paper aims to demonstrate how traditional ergonomic evaluation tools could be adapted to the use and assessment of exoskeletons in an existing DHM tool.

Figure 1 Illustration of human-exoskeleton interaction, adapted from Wolf et al. (2020)



2 Method

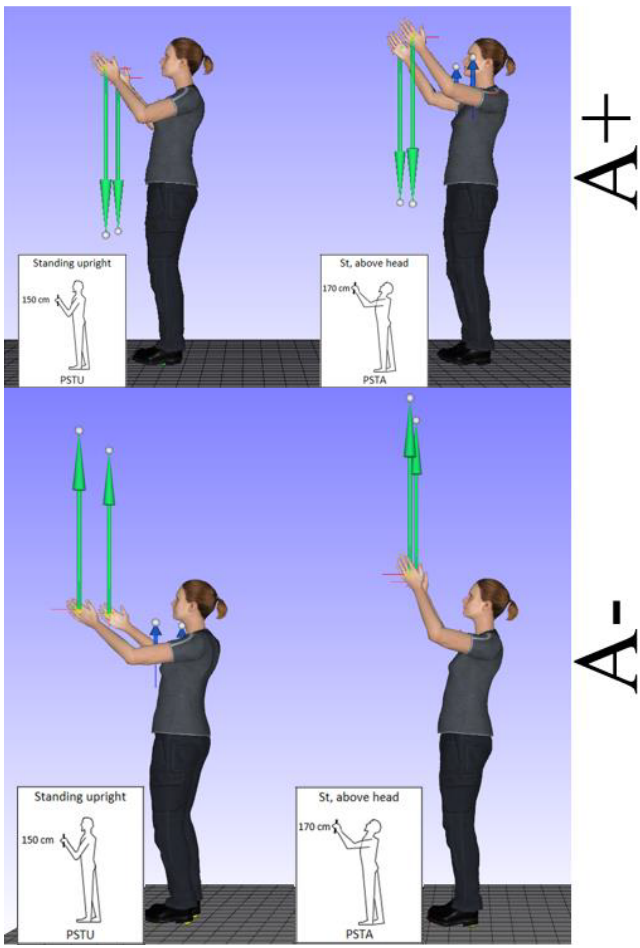
2.1 Methods for integrating DHM and exoskeleton simulations

In order to use DHM tools to assess the ergonomic effects of exoskeletons on workers, it is necessary to understand the kinds of interaction models typically used in DHM tools. According to Wolf et al. (2020), there are three approaches to modelling interactions between virtual products and virtual humans: predicting human behaviour as a function of product behaviour, predicting product behaviour as a function of pre-defined human behaviour, and predicting human and product behaviour as a mutually dependent feedback loop. While any of these approaches may be used to produce valid DHM results, we will focus on an approach that predicts human behaviour as a function of pre-defined product behaviour. A product can be any object that the manikin interacts with. Using this approach, product paths (the product's motion from the initial to the final position) are defined independently of the manikin or biomechanical constraints. The DHM tool then attempts to find a valid posture (via an inverse kinematics solver) or behaviour solution given that product motion path. A single posture is predicted in the limited case where the product path has only one position, and a product path will be referred to as a product state in this case. Figure 2 shows simulations of the manikin performing work in both exoskeleton and non-exoskeleton conditions, aligning with the postures and force directions specified in the ASFA.

Thus, in the current approach, the exoskeleton's behaviour (represented as forces acting on the manikin) is predicted as a result of a given posture, which in turn is the result of a product state (Figure 3). This approach assumes that the exoskeleton's relationship to the body can be known for any given posture and some set of static forces applied to the body at the relevant contact points.

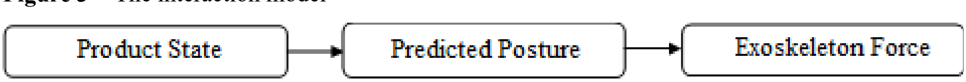
The DHM tool used for the simulations was IPS IMMA version 3.11 (Industrial Path Solutions, Gothenburg, Sweden). The manikin postures in IPS IMMA are generated by an inverse kinematics solver where a comfort function seeks to optimise comfort while fulfilling current constraints (assuring physiologically feasible postures) and where forces are treated by quasi-static methods (Bohlin et al., 2012). While a dynamic force simulation is preferred for a complete picture of exoskeleton effects on workers, the ASFA evaluation tool provides feedback on force-joint torque relationships for a specific set of static postures. Thus, for the current work, as long as static forces can be calculated for a specific posture and static joint torques calculated as the resultant of those forces, the DHM tool should be able to represent the impacts of an exoskeleton on a manikin in terms of the ASFA.

Figure 2 Examples of work situations simulated (see online version for colours)



Notes: PSTU_A+ without exoskeleton (upper left), PSTA_A+ (upper right) with exoskeleton support force on upper arms (blue arrows), PSTU_A– with exoskeleton (lower left) and PSTA_A– without exoskeleton (lower right). Green arrows mark external forces applied to hands

Figure 3 The interaction model



Upper body exoskeletons come in various designs and apply support forces in different locations on the users' bodies, typically along the arms, the shoulders, and lower back (usually the weight of the device, since the exoskeletons typically rest on the lower back using a belt). Further, force vectors and profiles can vary between exoskeletons and exoskeleton calibrations based on user needs. In order to simulate an exoskeleton in a DHM tool, it is necessary to know where the exoskeleton applies forces to the body and which forces it applies. The Ottobock Paexo Shoulder (Paexo) exoskeleton (Ottobock, Berlin, Germany), used in this study, is a passive upper-body exoskeleton that supports arm motions by applying forces to a point along each upper arm between the elbow and shoulder, typically in the middle of the upper arm. The forces are applied perpendicular to the long axis of the humerus bone from underneath the arm (below the triceps muscle). Forces are applied according to a nonlinear force profile driven by the extension/flexion angle of the shoulder joint θ_{sf} such that

$$v_u = f\left(\theta_{sf}\right) \tag{1}$$

where v_u is a force vector applied to the upper arm. For the current case, v_u is a three-dimensional vector defined by $v_u = (0, F_{\perp u}, 0)$ where $F_{\perp u}$ is a force applied perpendicular to the long axis of the humerus as described above. The parallel and lateral force values are assumed to be 0 as the Paexo does not apply forces in those directions. The precise mathematical description of a given exoskeleton depends on the design of the exoskeleton and the specific use case, along with the physical properties of the exoskeleton, defined by the force profile. The formulation of $f(\theta_{sf})$ may include additional terms such as gravity, limb segment masses, exoskeleton weight, or user strength to predict the force support provided by a given exoskeleton. The force profile may be derived from technical literature on a given exoskeleton or from empirical tests of an exoskeleton.

In the DHM software, the forces produced by the exoskeleton for a given posture can be specified by equation (1), where the DHM software provides the value of θ_{sf}. The flow of the simulation then begins by specifying a product state. The DHM tool then predicts a manikin posture for the product state using the relevant biomechanical angles to predict a force vector that the exoskeleton would apply given the predicted posture. If the DHM tool predicts both joint angles and joint torques, the predicted joint torques can be adjusted according to the force applied by the exoskeleton. The predicted joint torques can provide insight into the amount of potential effort reduction for that posture while wearing the exoskeleton. While this on its own may be a helpful insight, the reduction of required joint torque can also be used to assess the ergonomic benefit of the exoskeleton in the context of the ASFA assessment.

2.2 Method to assess ergonomics

The ASFA tool is used in this study as a guideline to assess work tasks regarding force exertion, with and without using an exoskeleton. The recommendations of maximum hand forces, and the corresponding risk levels, in ASFA, are developed to assess force exertion without using any assistive device, such as an exoskeleton. Based on the assumption that the shoulder joint strength demand is the limiting factor, we assume that the force threshold values recommended by the ASFA tool will be affected due to the effect of the exoskeleton. The study aims to investigate this assumption in more detail by the use of a DHM tool. Since overhead work is a common application for exoskeletons, the focus is on upper limbs exoskeletons that assist overhead work. Thus, we assume that the operator is standing and is applying force parallel to the body. We chose to study these four work situations out of the 54 work situations included in ASFA:

- Posture standing, upright work (PSTU), human is applying force in an upwards direction, 150 cm vertically from the floor (here denoted *PSTU_A+*).
- Posture standing, upright work, human is applying force in downwards direction, 150 cm vertically from the floor (here denoted *PSTU_A–*).
- Posture standing, above head work (PSTA), human is applying force in an upwards direction, 170 cm vertically from the floor (here denoted *PSTA_A+*).
- Posture standing, above head work, human is applying force in downwards direction, 170 cm vertically from the floor (here denoted *PSTA_A–*).

As for the force magnitudes, we chose to investigate the threshold forces between the risk levels green and yellow, and between yellow and red, according to the maximum recommended forces of ASFA and the risk levels of EN 1005-3:2002+A1:2008 (2008). To clarify, the threshold force between the risk level green and yellow was achieved by multiplying the maximum recommended force with 0.7, and the threshold force between the risk level yellow and red by multiplying the maximum recommended force with 0.5. According to EN 1005-3:2002+A1:2008 (2008), a value ratio of ≤0.5 is green (low risk/ recommended), a ratio between 0.5 and 0.7 is yellow (possible risk/not recommended), and a ratio of ≥0.7 is red (high risk/to be avoided). As recommended by ASFA, for design/planning, the 15th force percentile was used for defining the maximum recommended forces. In regards to the factors used in ASFA, for this study, the age factor (P1) was set to 1 (i.e., assumed the age of the operator/population to be around 30 years of age), and the gender factor (P2) was set to 0.5 (i.e., assuming a female or mixed-gender population). The frequency factor (T1) was set to 1 (i.e., assuming no frequency of force exertion), the biomechanics factor (T2) was set to 1 (i.e., symmetric load, two-handed force exertion), and the physiology factor (T3) was set to 1 (i.e., no frequent force exertions in unfavourable working postures, or force exertions within long-lasting periods in unfavourable working postures). As this is a comparative study looking at effects with and without exoskeleton, the choice of values for the factors is not as important as using the same values for each compared case.

Table 1 Forces per work situation (posture and force direction) and risk levels

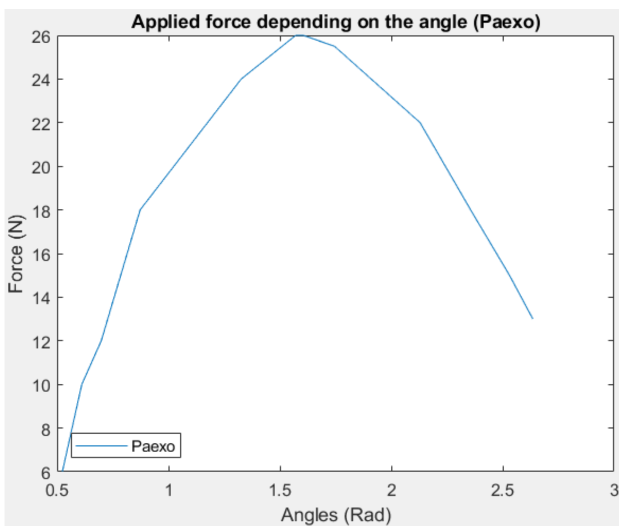
Work situation	PSTU_A+		PSTU_A–		PSTA_A+		PSTA_A–	
Original max rec. force (N)	190		203		180		205	
Risk level EN 1005-3	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow
Threshold factor	0.5	0.7	0.5	0.7	0.5	0.7	0.5	0.7
Force per hand, F_H (N)	47.5	66.5	50.8	71.1	45	63	51.3	71.8

Table 1 shows the maximum force per hand F_H (i.e., half of the recommended force exerted by each hand), given by the ASFA tool, considering the risk levels described above. The forces listed in the lower row in Table 1 were used in the DHM simulation as the external hand forces applied for the four work situations when not using an exoskeleton. The external forces were applied in the opposite direction to the forces applied by the manikin, meaning that the manikin needed to apply an equal magnitude force in the opposite direction, i.e., in direction A+ or A–, to keep equilibrium (Figure 2). For each work situation, by reading the torque in the shoulder joint in the DHM tool and considering that specific torque value as the limiting factor, i.e., not to be exceeded, we could calculate a corresponding assumed max external hand force when using an exoskeleton, i.e., with consideration of the force the exoskeleton provides on the upper arms, that would cause the same joint torque.

2.3 Simulation in DHM tool

A female manikin with a stature of 162 cm was created in IPS IMMA, corresponding to the 50th percentile in the ANSUR anthropometric database (Gordon et al., 1989). The remaining anthropometric dimensions were automatically predicted by IPS IMMA (Brolin et al., 2019).

Figure 4 Illustration of the force-angle relation of the exoskeleton (see online version for colours)



Each of the four selected ASFA work situations (PSTU_A+, PSTU_A–, PSTA_A+ and PSTA_A–) was setup in the DHM tool. Two product attachment points were created, one on each hand, where the external forces were applied. For each work situation, the corresponding force F_H in Table 1 was applied on the manikin. With that, we obtained the associated shoulder joint torque T when not using an exoskeleton.

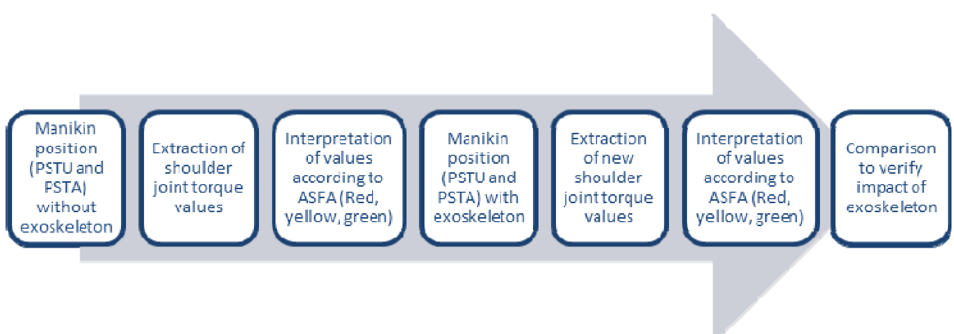
The next step was to add the exoskeleton model to the manikin. It was accomplished by using a scripted function that simulated the application of force $F_{\perp u}$ on the upper arms of the manikin. The specific form of the function in equation (1) was derived by measuring the force characteristics of the Paexo exoskeleton with an assumed typical calibration. The force was measured in several positions by using a goniometer to measure the exoskeleton angle and a dynamometer to measure the force. With the extracted values, we built a function relating the exoskeleton position and the force applied in that position that was transferred to the digital model. Figure 4 shows the values that were measured for an assumed typical calibration in the Paexo Shoulder exoskeleton.

Figure 2 illustrates how external forces were applied to the manikin for different work situations, where the blue arrows in the upper arms of the right manikin illustrate the force $F_{\perp u}$ acting on the manikin. With the force $F_{\perp u}$ applied to the upper arms, hand force F was adjusted so that the shoulder joint torque while wearing an exoskeleton, T_x, became close to the shoulder joint torque while not wearing an exoskeleton, T. The resultant force F_x causing a corresponding joint torque could be read from the DHM tool. Hence, based on the given assumptions, F_x would represent how the exoskeleton affects the maximum recommended hand force.

3 Results

By following the process in Figure 5, we obtained the data shown in Tables 2 and 3 for work situations PSTU (150 cm) and PSTA (170 cm), respectively, without and with exoskeleton. The tables show the hand force direction, the maximum recommended hand force, and the corresponding comparative shoulder joint torques for green and yellow threshold values of EN 1005-3:2002+A1:2008 (2008) within the ASFA. The difference in magnitude, as well as ratio, between F_H and F_x are provided to ease the analysis of the effects of the exoskeleton on the maximum recommended hand force.

Figure 5 Flowchart of the followed process to verify the impact of exoskeleton (see online version for colours)



The maximum recommended hand forces given in Tables 2 and 3 are per hand. Also, the values are reduced by 0.5 and 0.7, respectively, to correspond with the green and yellow risk levels of EN 1005-3:2002+A1:2008 (2008). To ease comparison with the non-reduced maximum recommended forces given by ASFA (upper row in Table 1), Table 4 shows the original ASFA values (still with factor P2 = 0.5) together with F_x modified to the total force (both hands) and non-reduced in regards to risk levels. For each work situation, the average value of the modified F_x value drawn from the green and yellow risk level results in Tables 2 and 3 was calculated.

Table 2 Maximum recommended hand forces and corresponding shoulder joint torques, with and without exoskeleton, for work situation PSTU

Hand force direction	*Threshold level*	*Without exoskeleton*		*With exoskeleton*		*$F_x - F_H$ (N)*	*F_x/F_H*
		Hand force F_H (N)	*Shoulder torque T (Nm)*	*Hand force F_H (N)*	*Shoulder torque T (Nm)*		
A+	Green	47.5	22.4	55.9	23.1	8.4	1.18
	Yellow	66.5	28.7	75.4	28.2	8.9	1.13
A–	Green	50.8	10.2	38.1	9.3	–12.7	0.75
	Yellow	71.1	16.9	59.2	20.3	–11.9	0.83

Table 3 Maximum recommended hand forces and corresponding shoulder joint torques, with and without exoskeleton, for work situation PSTA

Hand force direction	*Threshold level*	*Without exoskeleton*		*With exoskeleton*		*$F_x - F_H$ (N)*	*F_x/F_H*
		Hand force F_H (N)	*Shoulder torque T (Nm)*	*Hand force F_H (N)*	*Shoulder torque T (Nm)*		
A+	Green	45	21.2	51.1	20.6	6.1	1.13
	Yellow	63	27	69.5	26.5	6.5	1.10
A–	Green	51.3	9.5	40.5	8.6	–10.8	0.79
	Yellow	71.8	16	61.9	15.4	–9.9	0.86

Table 4 Comparison of the original maximum recommended hand forces of the ASFA with the modified maximum recommended hand forces when using an exoskeleton

Work situation	*PSTU_A+*	*PSTU_A–*	*PSTA_A+*	*PSTA_A–*
Original ASFA max rec. force without exoskeleton, F_O (N)	190	203	180	205
Modified max rec. force with exoskeleton, F_M (N)	219	161	201	169
$F_M - F_O$ (*N*)	29	–42	21	–36
F_M/F_O	1.15	0.79	1.12	0.82

4 Discussion

The study aimed to demonstrate a methodology for simulating and evaluating exoskeletons using a DHM tool environment. While different DHM tools have different capabilities relating to exoskeleton simulations, there is, as of yet, little discussion of methods for evaluating exoskeletons using DHM or similar simulation tools. We have proposed the ASFA as one candidate evaluation tool which can provide a standard for comparing potential exoskeleton solutions. While the ASFA is limited in this application to specific use contexts and it is based on force levels measured from the male population, it also provides a clear set of standards as well as a correction factor for female or mixed-gender populations (which was applied in this study, see factor P2 in Subsection 2.2), and its use of fixed postures and factors makes it relatively straightforward to apply for exoskeleton comparisons. In the study, we were able to produce the expected simulation results and adjust the simulation in order to produce values that could be compared within the ASFA evaluation tool. While we believe the demonstrated approach is useful for supporting decisions related to exoskeletons in production, the study also highlighted several challenges presented themselves.

In the study, we used a specific exoskeleton and a single manikin representing the 50th percentile female worker. Moreover, the exoskeleton could be calibrated to specific user needs, and the exoskeleton model reflected only a single calibration. Although the results are assumed to be similar in different cases with the same system, the study results are limited and should correspondingly not be interpreted too broadly. Different exoskeletons, calibrations, users, and workstation configurations are likely to lead to different results. Although the conditions of this study are particular to our Paexo Shoulder exoskeleton, the results provide a good insight into how the different postures within ASFA and the different force directions affect the shoulder joint torque and hand forces. Our objective is to present an initial framework for how an ergonomics evaluation tool can be adapted to the use of an exoskeleton. This is not to say that the results or proposed methods are meaningless. Instead, it highlights the importance of considering as wide a range of use cases, scenarios and aspects as possible. For instance, there are many additional ergonomics factors that are likely to influence decisions to implement exoskeletons, and their acceptance by end-users, e.g., comfort, collisions, and adjustability. While certain aspects, such as comfort, are subjective and difficult to simulate, even though there are simplified methods to assess comfort by looking at joint angles, DHM tools are well-suited to study other aspects of exoskeleton's implementation, such as possible collisions between the human body and the exoskeleton, and with the surrounding environment. Stakeholders can specify and explore possibilities using DHM tools in order to get a better perspective on the impact of various exoskeletons on worker well-being and system performance. One core advantage of DHM simulation tools is that they are often explicitly designed to allow for this kind of explorative evaluation, testing multiple scenarios and potential users *in silico* before moving to physical tests and validation.

As noted in Section 2, the study is based on the assumption that the shoulder joint strength demand is the limiting factor. Hence, we consider each entire arm as rigid body, and we only consider the changes in the torque magnitude in the glenohumeral joint. This biomechanical simplification can be questioned. Increased forces in hands, possible thanks to the exoskeleton support, will indeed cause increased loads on the hand and the arm, e.g., in the wrist and the elbow joint. Future studies should consider the assessment of the effects also on the hands and arms, and preferably the effects of the exoskeleton on the entire human biomechanical system.

Exoskeletons introduce an extra weight load, typically applied mainly on the lower back since most upper body exoskeletons are attached with belt-like systems. This extra weight was not considered in this study. Still, the Paexo Shoulder exoskeleton used in this study is comparatively light, with a weight of approximately 1.9 kg (Ottobock, Berlin, Germany).

In the DHM simulations, we created a manikin according to the 50th percentile female manikin from the ANSUR anthropometric database (Gordon et al., 1989). This database is old but widespread and generally available. Still, in future studies, it will be beneficial to use a more recent anthropometric database and also to create a family of manikins as virtual test subjects in order to better represent the target population.

As discussed previously in Rivera et al. (2021), exoskeletons have different physical and mechanical properties, affecting how and where forces are applied to the user. Further, calibration options may make a given exoskeleton's exact force support properties challenging to simulate precisely. The additional lack of documentation of exoskeleton properties or agreed standards in exoskeleton specifications often means that detailed simulations require empirical measurements. If the simulations aim to support decisions regarding which not-yet-purchased exoskeleton is best suited to a production context, the stakeholders face a bit of a 'chicken and egg' problem. If DHM and similar simulation tools are to be put into widespread use for this kind of decision support, better exoskeleton documentation and specification standards are needed.

Another challenge involves the limits of physics predictions in the exoskeleton simulations. In our study, we should be able to estimate a force on hands while wearing the exoskeleton that will result in a shoulder joint torque equivalent to a given torque produced when no exoskeleton is worn. However, as can be seen in Tables 2 and 3, there were some differences between T and T_x. There may be multiple factors that caused this, where one is assumed to be the optimisation-based posture prediction utilised by the selected DHM tool (IPS IMMA), which may select slightly different postures when the upper arm forces of the exoskeleton are simulated. Efforts were taken to avoid simulated posture differences, but the nature of the inverse kinematics solvers implemented in many DHM tools means that complete control of posture predictions is not possible in every situation. Finally, minor errors may have been exaggerated due to floating-point errors in the underlying code of the simulation systems. It is worth noting that DHM tools are overall quite precise and capable of posture prediction, but in this case, even minimal errors could have unexpected effects, though we do not expect them to be significant.

Considering these challenges, we can also identify some interesting insights from the exploratory study. Because the work situations PSTU and PSTA involve different arm positions, the exoskeleton applies different force magnitudes in each situation, and the joint torque implications are thus different. The green threshold force for PTSU in the A+ direction is increased by 8.4 N, but for PSTA, it is increased by 6.1 N. Since the arms are held higher in the PSTA posture, these numbers fit with the experienced force profile of the Paexo Shoulder exoskeleton, which provides maximum support at a roughly 90 degrees arm elevation (closer to PSTU in this case). Another finding is that the exoskeleton reduces the maximum recommended force in force direction A–. This may be obvious since, in this case, the exoskeleton hinders the human from performing the task. Indeed, the Paexo Shoulder exoskeleton is designed to give force support in an upwards direction, but still, it is a valuable finding since it highlights the concerns that may occur if a work task sequence requires the human to exert forces in varying directions. In such case, the use, or the design of the exoskeleton, would need to be modified to suit the nature of the work, e.g., with a function to turn on and off the force support. This kind of qualitative insight can be beneficial when considering whether to introduce an exoskeleton or deciding between exoskeleton solutions. Especially if specific postures and force directions are more or less likely within a production task. These insights could be further improved if multiple ASFA work situations are mapped to the target production task and are used to provide insights into how well a given exoskeleton will keep forces within acceptable levels.

5 Conclusions

This paper proposes a general method for evaluating the ergonomic effects of introducing an exoskeleton in a production context using DHM simulation tools and an existing ergonomic assessment framework. In general form, we believe this kind of methodology and the corresponding workflow can be helpful for decision-makers and stakeholders considering implementing exoskeletons in a production environment. Using DHM simulation tools provides the ability to test multiple exoskeletons and workstations without time-consuming and costly tests with actual equipment and workstations. DHM tools also allow for considering different anthropometries ensuring insights that benefit a more diverse workforce. Moreover, using the simulation results to update recommendations from existing ergonomics evaluation methods allows for decisions to be made with existing known tools. As new evaluation methods are developed that consider exoskeleton evaluation from inception, this later advantage will be likely less valuable. The overall aim of implementing quantitative and comparable evaluation metrics for exoskeletons in DHM tools is a valuable endeavour and one we believe can only benefit production design, exoskeleton development, and (most importantly) workers.

Acknowledgements

This work has been made possible with the support from the Knowledge Foundation supported research environment INFINIT at the University of Skövde, in the project Synergy Virtual Ergonomics (SVE), Recruitment and Strategic Knowledge Reinforcement initiative and with support from VINNOVA in the project VIVA – the Virtual Vehicle Assembler, and by the participating organisations. This support is gratefully acknowledged.

References

Baltrusch, S.J., van Dieën, J.H., van Bennekom, C.A.M. and Houdijk, H. (2018) 'The effect of a passive trunk exoskeleton on functional performance in healthy individuals', *Applied Ergonomics*, Vol. 72, pp.94–106, https://doi.org/10.1016/j.apergo.2018.04.007.

Bohlin, R., Delfs, N., Hanson, L., Högberg, D. and Carlson, J.S. (2012) 'Automatic creation of virtual manikin motions maximizing comfort in manual assembly processes', in Hu, S.J. (Ed.): *Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems*, pp.209–212.

Bornmann, J., Schirrmeister, B., Parth, T. and Gonzalez-Vargas, J. (2020) 'Comprehensive development, implementation and evaluation of industrial exoskeletons', *Current Directions in Biomedical Engineering*, Vol. 6, No. 2 [online] https://doi.org/10.1515/cdbme-2020-2001.

Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2019) 'Development and evaluation of an anthropometric module for digital human modelling systems', *International Journal of Human Factors Modelling and Simulation*, Vol. 7, No. 1, pp.47–70 [online] http://dx.doi.org/10.1504/IJHFMS.2019.102178.

de Vries, A., Murphy, M., Könemann, R., Kingma, I. and de Looze, M. (2019) 'The amount of support provided by a passive arm support exoskeleton in a range of elevated arm postures', *IISE Transactions on Occupational Ergonomics and Human Factors*, Vol. 7, Nos. 3–4, pp.311–321 [online] https://doi.org/10.1080/24725838.2019.1669736.

Demirel, H.O., Salman Ahmed, S. and Duffy, V.G. (2021) 'Digital human modeling: a review and reappraisal of origins, present, and expected future methods for representing humans computationally', *International Journal of Human-Computer Interaction*, DOI: 10.1080/10447318.2021.1976507.

EN 1005-3:2002+A1:2008 (2008) *Safety of Machinery – Human Physical Performance – Part 3: Recommended Force Limits for Machinery Operation*.

Fritzsche, L., Galibarov, P., Gärtner, C., Bornmann, J., Damsgaard, M., Wall, R., Schirrmeister, B., Gonzalez-Vargas, J., Pucci, D., Maurice, P., Ivaldi, S. and Babič, J. (2021) 'Assessing the efficiency of exoskeletons in physical strain reduction by biomechanical simulation with AnyBody modeling system', *Wearable Technologies*, Vol. 2, p.E6, DOI: 10.1017/wtc.2021.5.

Gordon, C.C., Churchill, T., Clauser, C.E., Bradtmiller, B., Mcconville, J.T., Tebbetts, I. and Walker, R.A. (1989) *1988 Anthropometric Survey of US Army Personnel: Methods and Summary Statistics*, US Army Natick Research, Development and Engineering Center, Natick.

Gull, M.A., Bai, S. and Bak, T. (2020) 'A review on design of upper limb exoskeletons', *Robotics*, Vol. 9, No. 1, p.16 [online] https://doi.org/10.3390/robotics9010016.

Hall, A.D., La Delfa, N.J., Loma, C. and Potvin, J.R. (2021) 'A comparison between measured female linear arm strengths and estimates from the 3D Static Strength Prediction Program (3D SSPP)', *Applied Ergonomics*, Vol. 94, p.103415 [online] https://doi.org/10.1016/j.apergo.2021.103415.

Hignett, S. and McAtamney, L. (2000) 'Rapid Entire Body Assessment (REBA)', *Applied Ergonomics*, Vol. 31, No. 2, pp.201–205 [online] https://doi.org/10.1016/S0003-6870(99)00039-3.

Huysamen, K., Bosch, T., de Looze, M., Stadler, K.S., Graf, E. and O'Sullivan, L.W. (2018) 'Evaluation of a passive exoskeleton for static upper limb activities', *Applied Ergonomics*, Vol. 70, pp.148–155 [online] https://doi.org/10.1016/j.apergo.2018.02.009.

Karhu, O., Kansi, P. and Kuorinka, I. (1977) 'Correcting working postures in industry: a practical method for analysis', *Applied Ergonomics*, Vol. 8, No. 4, pp.199–201 [online] https://doi.org/10.1016/0003-6870(77)90164-8.

Kiguchi, K. and Hayashi, Y. (2012) 'An EMG-based control for an upper-limb power-assist exoskeleton robot', *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, Vol. 42, No. 4, pp.1064–1071 [online] https://doi.org/10.1109/TSMCB.2012.2185843.

Maurice, P., Camernik, J., Gorjan, D., Schirrmeister, B., Bornmann, J., Tagliapietra, L., Latella, C., Pucci, D., Fritzsche, L., Ivaldi, S. and Babic, J. (2020) 'Objective and subjective effects of a passive exoskeleton on overhead work', *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 28, No. 1, pp.152–164 [online] https://doi.org/10.1109/tnsre.2019.2945368.

McAtamney, L. and Corlett, E.N. (1993) 'RULA: a survey method for the investigation of work-related upper limb disorders', *Applied Ergonomics*, Vol. 24, No. 2, pp.91–99 [online] https://doi.org/10.1016/0003-6870(93)90080-S.

Perez Luque, E., Högberg, D., Iriondo Pascual, A., Lämkull, D. and Garcia Rivera, F. (2020) 'Motion behavior and range of motion when using exoskeletons in manual assembly tasks', in Säfsten, K. and Elgh, F. (Eds.): *SPS2020 – Proceedings of the 9th Swedish Production Symposium, Advances in Transdisciplinary Engineering*, Jönköping, Sweden, IOS Press, Amsterdam, 7–8 October, Vol. 13, pp. 217–228 [online] https://doi.org/10.3233/ATDE200159.

Rivera, F.G., Brolin, A., Luque, E.P. and Högberg, D. (2021) 'A framework to model the use of exoskeletons in DHM tools', in Wright, J.L., Barber, D., Scataglini, S. and Rajulu, S.L. (Eds.): *Advances in Simulation and Digital Human Modeling, Lecture Notes in Networks and Systems*, Springer International Publishing, Cham, pp.312–319 [online] https://doi.org/10.1007/978-3-030-79763-8_38.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015) *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*, Company Report, Boston Consulting Group.

Scataglini, S. and Paul, G. (2019) *DHM and Posturography*, Elsevier Academic [online] https://doi.org/10.1016/C2018-0-00529-0.

Schaub, K., Wakula, J., Berg, K., Kaiser, B., Bruder, R., Glitsch, U. and Ellegast, R-P. (2015) 'The Assembly Specific Force Atlas', *Human Factors and Ergonomics in Manufacturing & Service Industries*, Vol. 25, No. 3, pp.329–339 [online] https://doi.org/10.1002/hfm.20545.

Schaub, K.G., Mühlstedt, J., Illmann, B., Bauer, S., Fritzsche, L., Wagner, T., Bullinger-Hoffmann, A.C. and Bruder, R. (2012) 'Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet' (EAWS)', *International Journal of Human Factors Modelling and Simulation*, Vol. 3, Nos. 3/4, pp.398–426 [online] https://doi.org/10.1504/IJHFMS.2012.051581.

Schluse, M., Priggemeyer, M., Atorf, L. and Rossmann, J. (2018) 'Experimentable digital twins – streamlining simulation-based systems engineering for Industry 4.0', *IEEE Transactions on Industrial Informatics*, Vol. 14, No. 4, pp.1722–1731.

Schmalz, T., Schändlinger, J., Schuler, M., Bornmann, J., Schirrmeister, B., Kannenberg, A. and Ernst, M. (2019) 'Biomechanical and metabolic effectiveness of an industrial exoskeleton for overhead work', *International Journal of Environmental Research and Public Health*, Vol. 16, No. 23, p.4792 [online] https://doi.org/10.3390/ijerph16234792.

Tröster, M., Schneider, U., Bauernhansl, T., Rasmussen, J. and Andersen, M.S. (2018) 'Simulation framework for active upper limb exoskeleton design optimization based on musculoskeletal modeling', in *Technische Unterstützungssysteme, die die Menschen Wirklich Wollen*, pp.345–353, Helmut-Schmidt-Universität.

Waters, T.R., Putz-Anderson, V., Garg, A. and Fine, L.J. (1993) 'Revised NIOSH equation for the design and evaluation of manual lifting tasks', *Ergonomics*, Vol. 36, No. 7, pp.749–776 [online] https://doi.org/10.1080/00140139308967940.

Wolf, A., Miehling, J. and Wartzack, S. (2020) 'Challenges in interaction modelling with digital human models – a systematic literature review of interaction modelling approaches', *Ergonomics*, Vol. 63, No. 11, pp.1442–1458 [online] https://doi.org/10.1080/00140139.2020.1786606.

Zhou, X. (2020) 'Predictive human-in-the-loop simulations for assistive exoskeletons', in *Proceedings of the ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC2020-22668*.