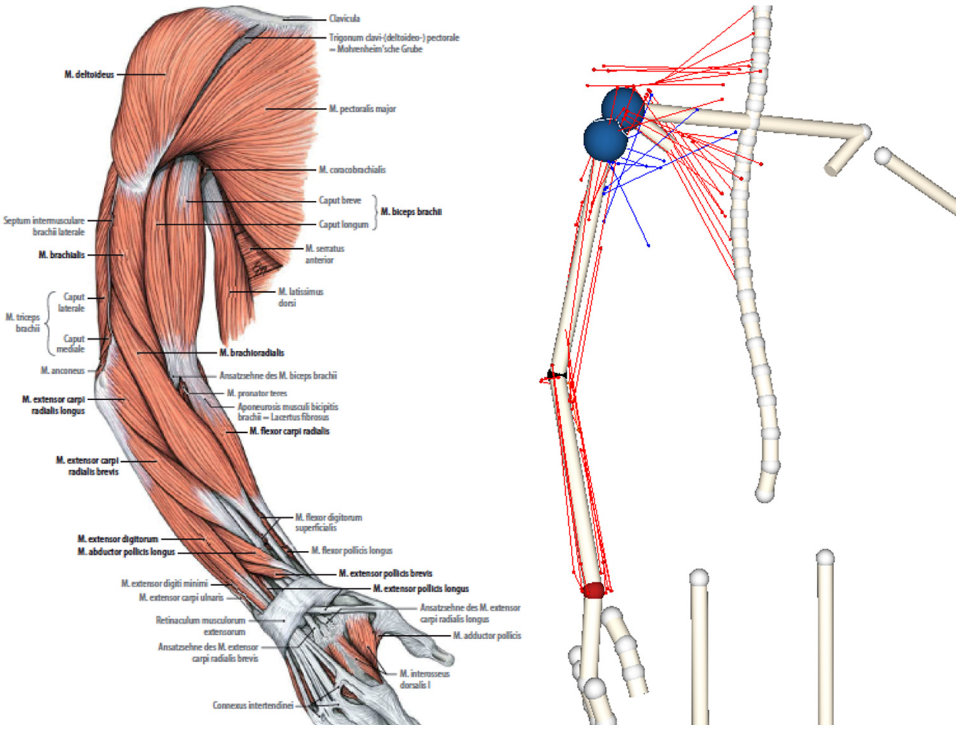
Final Report CROMM-Creation of Muscle Manikins

Dnr 2012-04584



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Datum: 2016-12-23

Delprogram: FFI Sustainable Production

FFI Fordonsstrategisk Forskning och Innovation

VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

Innehållsförteckning

Kort om FFI

FFI är ett samarbete mellan staten och fordonsindustrin om att gemensamt finansiera forsknings-, i nnovations- och utvecklingsaktiviteter med fokus på områdena Klimat & Miljö samt Säkerhet. Satsningen innebär verksamhet för ca 1 miljard kr per år varav de offentliga medlen utgör drygt 400 Mkr.

För närvarande finns fem delprogram; Energi & miljö, Trafiksäkerhet och automatiserade fordon, Elektronik, mjukvara och kommunikation, Hållbar produktion och Effektiva och uppkopplade transportsystem. Läs mer på www.vinnova.se/ffi

1 Sammanfattning (max 5000 tecken)

Europeiska och svenska forskningsutlysningar beskriver ett tydligt och stort behov av nya simulerings- och visualiseringsverktyg. De belyser även kommande demografiska utmaningar, där en trend är ökad livslängd. Det är således viktigt att framtida arbetsplatser utformas enligt inkluderande principer där miljö, verktyg och uppgifter är anpassade utifrån den variation som finns inom arbetskraften. Sverige har en världsledande tradition inom ergonomi. Vinnovas forskningsbeskrivning inom hållbar produktion belyser att denna position bör behållas och förstärkas, samt belyser behovet av virtuella verktyg för ergonomisimulering och design av arbetsplatser.

Arbetsrelaterade belastningsskador i muskler och skelett uppstår ofta till följd av att arbetsplatser inte utformas så att arbete kan utföras med god ergonomi. Biomekaniska modeller i ergonomisimuleringsverktyg som finns på marknaden saknar oftast modeller av muskler. Verktygen saknar därmed förmåga att förutsäga muskelbelastning och prediktera risker för arbetsrelaterade belastningsskador i muskler.

Det övergripande syftet med CROMM-projektet var att utveckla ett produktionstekniskt stödverktyg som:
1) automatiskt kan beräkna och visualisera en möjlig monteringsrörelse som minimerar den muskuloskeletala hälsoeffekten för arbetstagaren,
2) utför ergonomi- och tidsbalansering av arbetsuppgifter i en parallell process.

Dessutom syftade projektet till att vidareutveckla skelettversion av ergonomisimuleringsverktyget IMMA och introducera det i svenskt näringsliv.

Projektet var uppdelat i sex arbetspaket. Varje arbetspaket utvecklade kunskap som implementerades i demonstratorversioner av IMMA. Under projektet utvärderades demonstratorerna av industriella och akademiska partners. Demonstratorerna möjliggjorde löpande kommunikation, utvärdering och utveckling av verktyget. Inom projektkonsortiet definierades relevanta och utmanande användarscenarion. Dessa scenarion användes för att styra utvecklingen av stödverktyget och för att bekräfta uppfyllandet av projektmålen. Vid slutpresentationen illustrerades de utvecklade funktionerna i demonstratorn. Demonstratorn var vid slutpresentationen på en TRL-nivå runt 4 och innehöll:

- en biomekanisk modell med 35 muskler som verkar på axel, överarm, underarm och handled.
- en modell av människan som modelleras som ett dynamiskt system och använder optimala styrmetoder för att beräkna rörelser.
- metoder för att ta hänsyn till mänsklig variation inom kroppsmått, muskelstyrka och rörelseförmåga i leder.
- ergonomiska bedömningsmetoder för muskelaktivitet.

Ett monteringsscenario innehöll en första export- och importfunktion mellan IMMA-demonstratorn och tidsbalanseringsprogramvaran AviX. En monteringssekvens importerades från Avix in i IMMA. Den mänskliga modellen i IMMA utför uppgiften och med hjälp av ergonomibedömningsmetoder ges ergonomipoäng på varje arbetsmoment. Dessa ergonomipoäng skickas sedan tillbaka till AviX, där tider på arbetsmoment finns. Information om både tid och ergonomi tillgängligt i ett och samma verktyg möjliggör parallell balansering av produktionslinjen. Normalt utförs detta arbete i sekvens och iterativt, vilket är tidskrävande och ofta leder till bristfälliga lösningar.

Montering av en mittkonsol, ett säte och en elektronikenhet användes för att illustrera funktioner för skelett-IMMA. Skelettdemonstratorn nådde en TRL-nivå på ungefär 7. Under projektet genomfördes en mängd förbättringar av verktyget. Den biomekaniska modellen uppdaterades, de matematiska algoritmerna för rörelsegenerering förfinade, en modul för hantering av mångfald skapades, en event editor för styrning av den mänskliga modellen utvecklades och modulen för ergonomisk bedömning uppdaterades. Detta arbete byggde vidare på det som skapades i SSF-projektet Intelligently Moving Manikins, vilket skapade en utmärkt grund för det utvecklingsprojekt som följde, där resultatet integrerades i IPS plattform. Detta integrationsarbete ledde till skapandet av ergonomisimuleringsverktyget IPS IMMA. Arbetet finansierades av CEVT, Scania, Volvo Personvagnar och Volvo Lastvagnar som ett separat initiativ.

Resultaten från CROMM-projektet, och det parallella initiativet att realisera IPS IMMA, möjliggjorde att ett för användaren enkelt ergonomisimuleringsprogram levererats till fordonsindustrin, som efterfrågades i den svenska forskningsagendan. Den första grundversionen av IPS IMMA omfattar en biomekanisk modell som inkluderar skelettet. Ingen dynamik eller muskler finns tillgängligt i denna version. Den demonstrator på muskel, dynamik och personas som utvecklades i CROMM-projektet behöver mer forskning och utveckling innan den kan implementeras i IPS IMMA och levereras till industrin. Ett uppföljningsprojekt, VIVA –the Virtual Vehicle Assembler, som fokuserar på dessa aspekter plus nya forskningsutmaningar, har sänts in till Vinnova, Funktionerna som utvecklats mellan AviX och IMMA för parallell optimering av ergonomi och systemprestanda är intressanta och behöver utvecklas ytterligare. Ett förslag om ett uppföljningsprojekt har skickats till ITEA. Den svenska forskningsagendan beskriver ett behov av virtuella verktyg som kan optimera flera parametrar i en parallell process.

Projektet också resulterat i sex vetenskapliga tidskrifter och 16 konferensbidrag. Två doktorander försvarade sina doktorsavhandlingar inom ramen för projektet och 4 studenter genomförde sina examensarbete inom projektet. Ett avknoppningsföretag har startats.

2 Executive summary

Both European and Swedish research agendas describe a clear and huge need of new modelling, simulation and forecasting methods and tools. The European agendas also highlight coming demographic challenges, where one trend is increasing life expectancy. Thus it becomes vital that manufacturing workplaces are created according to inclusive design principles where environment, tools and tasks are designed to cater for a wide variation range within the workforce. Sweden have a world leading tradition within human centred design and ergonomics and Vinnova's Sustainable Production document points out that this position should be kept and strengthened without ignoring productivity and competiveness. Within the Swedish research agenda virtual tools for ergonomics simulation and workplace design is even explicitly mentioned as a desired research result.

Within the physical world of ergonomics, work-related musculoskeletal disorders is a common expression for issues related to problems arising from work not being designed and performed in accordance to good ergonomics principles from a physical perspective.

The digital human modelling tools available on the market are not able to predict skeletal and muscles exposures, and hence has no functionality to predict likely human response on work tasks being simulated in the tools. One major reason for this is that the biomechanical models in the DHM tools do not include models of muscles.

The overall aim was to develop a supportive production engineering tool which can:

1) automatically compute and visualise a possible assembly motion that minimises the musculoskeletal health effect on workers,
2) perform ergonomics and time balancing of work tasks between workers and workstations.

Furthermore, the proposed project aimed to implement the digital human modelling tool IMMA in Swedish industry and universities.

The project was divided into six work packages that led the project towards the final objectives. From each work package, knowledge was developed and implemented in a demonstrator version of IMMA. Throughout the project, demonstrators were refined, tested and evaluated by industrial and academic partners. The demonstrator development was essential within the project, where the demonstrator supported communication, assessment and refinement of the tool. Within the project consortia, relevant and challenging uses cases were defined. These use cases were used to feed the development of the tool and to confirm fulfilment of project objectives. The new functions of the tool were illustrated at the final presentation meeting. The demonstrator is at a lower TRL level, approximately 4. The demonstrator includes:

- a manikin equipped with 35 muscles that act on the shoulder, upper arm, forearm and wrist.
- the manikin modelled as a dynamical system and optimal control methods to compute the motions.
- methods for the consideration of human variation of body dimension, muscle strength and joint range of motions.
- ergonomics assessment methods to consider muscle activity.

One use case illustrated a first export and import function developed between the IMMA demonstrator and Avix. An assembly sequence was imported in the event editor that controls the manikin. The manikin performs the tasks and the IMMA demonstrator, using the ergonomics assessment module, adds an ergonomics score on each task. Sending this information of ergonomics scores and time back to Avix, it is possible to balance the production line related to ergonomics and time in parallel.

Assembly of a centre console, a seat and an electronics unit were used to illustrate functions for the IMMA skeleton demonstrator on a higher TRL level, approximately 7. During the project, several updates were made to the IMMA skeleton demonstrator: the structure of the biomechanical model, mathematic algorithms for motion generation, module to handle human diversity, event editor for controlling the manikin and module for ergonomic assessment. This work had its basis in results from the SSF funded project Intelligently Moving Manikins. The work done in this work package created an excellent basis for the development that followed, where the demonstrator was integrated in the IPS (Industrial Path Solutions) platform. This integration work, realising a first version of the digital human modelling tool IPS IMMA, was financially funded by CEVT, Scania, Volvo Cars and Volvo Trucks as a separate initiative.

The results from the CROMM project, and the implementation project of developing and introducing IPS IMMA, is the first basic delivery to the industry of an ergonomics simulation tool, which is mentioned as a need in the Swedish research agenda. The first basic version of IPS IMMA includes a biomechanical model including the skeleton. No dynamics or muscles are however yet implemented. The demonstrator on muscles, dynamics and personas developed in the CROMM project needs more research and development before it can be implemented in the IPS IMMA and delivered to industry. A follow-up project, VIVA – the Virtual Vehicle Assembler, focuses on these aspects, and a project application have been submitted to Vinnova. The work introduced in the CROMM project between Avix and IMMA for the concurrent balancing of ergonomics and time is interesting and needs to be further investigated. A proposal on a follow-up project has been submitted to an ITEA call. The Swedish research agenda asks for such virtual tool, able to optimise several parameters in a parallel process.

The project has also resulted in six scientific journal papers and 16 conference papers. Two PhD students defended their doctoral theses, and 4 students did their master or bachelor thesis projects, within the project. One spin-off company was started.

3 Background

Both European (EFFRA, 2012) and Swedish (Vinnova, 2011) research agendas describe a clear and huge need of new modelling, simulation and forecasting methods and tools. The research organisations formulate these after compiling result from academic and industry discussions, including the Swedish automotive industry. The tools are needed for design, modelling, simulation, optimisation and forecasting of production processes, resources, systems and factories during their life-cycle. Digital factory models need to be created before the real factory is implemented to explore different design options, evaluate their performance and virtually commission automation system and verify the manual systems, thus reducing critical time-to production and supporting superior production performance. Furthermore, virtual factory models needs to be maintained throughout the lifetime of the production to guarantee an effective and efficient connection and consistency with the real factory on the shop floor. In addition, reconfiguration options need to be tested in the virtual factory with the use of modelling and simulation tools and then, after validation, the changes are implemented in the real factory in a short time. The evolution of the real factory will be reflected and stored into the virtual models of the factory.

The European (EFFRA, 2012) agendas also highlight coming demographic challenges, where one trend is increasing life expectancy. A related change is the increasing proportion of elderly people in the society. Due to this, governments in Europe and Sweden discuss to raise retirement ages gradually to ensure that their national pension systems are both affordable and adequate. This in turn means that the number of elderly people in organizations’ workforces will increase, also in the Swedish automotive industry. Thus it becomes vital that manufacturing workplaces are created according to inclusive design principles where environment, tools and tasks are designed to cater for a wide variation range within the workforce, e.g. related to physical and cognitive capabilities of workers. There are several objectives of such an approach, where, from a production management perspective, inclusive workplaces support flexibility, performance and robustness of the manufacturing facilities. Future workplaces should indeed enable high performance and quality output, but should also be attractive in the eye of the operator to support recruitments of high skilled employees and to enable that employments can be kept within Europe and Sweden. Sweden have a world leading tradition within human centred design and ergonomics and Vinnova's Sustainable Production document (Vinnova, 2011) points out that this position should be kept and strengthened without ignoring productivity and competiveness. Ergonomics is today mainly verified with physical prototypes of products and production systems, hence typically using a reactive approach towards identifying problems and finding solutions. However, there exist a number of commercial digital human modelling (DHM) tools on the market that supports a proactive approach towards human centric design of products and workplaces. The Swedish industry is using these tools to some extent. DHM tools fit within a framework of virtual ergonomics or sustainable and work environment, which is pointed out as a prioritized area in Vinnova's road map document (Vinnova, 2012).

Within the physical world of ergonomics, work-related musculoskeletal disorders (WMSDs) is a common expression for issues related to problems arising from work not being designed and performed in accordance to good ergonomics principles from a physical perspective (e.g. Kuorinka, 1998; Karsh and Smith, 2006). Several studies exist, e.g. Nordander et al. (2013), where products and production systems are ergonomically assessed by measuring skeletal and muscle exposure, and then examining human response from those exposures. These two information sources are then set together to establish dose-response relations. The digital human modelling tools available on the market are not able to predict skeletal and muscles exposures, and hence has no functionality to predict likely human response on work tasks being simulated in the tools. One major reason for this is that the biomechanical models in the DHM tools do not include models of muscles. The biomechanical model is rather a simplified skeletal model of the human body built up by segments and joints. Exceptions exist though. The tool *Jack* (Badler, 1993) calculates muscles forces for few selected muscles by using mathematic algorithms. *Anybody* (Rasmussen et al., 2002) is the DHM tool on the market with the most complete muscle models. However, this is an expert tool with no support for assembly planning and it is not used by common engineers in industry. Furthermore, the existing DHM tools focus on one worker carrying out a specific task in a given workstation. In industry though, assembly tasks are time balanced over several workstations to get an efficient production process. No DHM tool on the market is able to consider this kind of productivity balancing. Therefore there is a need for an efficient and easy to use DHM tool that can visualise and predict musculoskeletal exposures and at the same time balance worker exposure and production effeciency.

4 Aim and method

The overall aim was to develop a supportive production engineering tool which can:

3) automatically compute and visualise a possible assembly motion that minimises the musculoskeletal health effect on workers,
4) perform ergonomics and time balancing of work tasks between workers and workstations.

Furthermore, the proposed project aimed to implement the digital human modelling tool IMMA in Swedish industry and universities.

The project was divided into six work packages that led the project towards the final objectives. From each work package, knowledge was developed and implemented in a demonstrator version of IMMA. Throughout the project, the demonstrator was refined, tested and evaluated by industrial and academic partners. Realistic and challenging use cases at collaborating companies were used to verify outcomes and provide feedback for further developments. A final version of the IMMA based production engineering tool was delivered to allow for implementation and utilisation at partner companies and universities.

5 Project objectives

The project was divided into six work packages with specific objectives. The work packages were described in detail in the application. This chapter presents the overall objectives of each work package. No major modification of objectives was made during the project.

WP1: Project coordination and demonstrator development
The objective of the work package was to manage the project. The work package was also responsible for managing demonstrator development and production of scientific papers.

WP2: Manikin dynamics and muscle model development
The objective of the work package was develop functionality to simulate manikin dynamics and to equip the manikin with muscle models. This included development of functionality to model the manikin as a dynamical system, as well as modelling of muscles, with a focus on the shoulder and forearm muscles since these body regions often are problematic from a WMSD perspective.

WP3: Methods for the consideration of human variation (strength and range-of-motion)
The objective of the work package was to investigate which other parameters than anthropometric length measures that are affecting human assembly work and how they can be considered in a simulation. This since muscle strength is one possible factor that may influence human behaviour and the risks for obtaining WMSDs.

WP4: Assessment methods considering muscle activity
The objective of the work package was to develop kinetic ergonomics assessment methods and to implement methods to optimize the biomechanical load in the muscles during an assembly task.

WP5: Ergonomics and productivity balancing
The objective of the work package was to develop a production balancing module, based on the IMMA tool, where traditional production parameters are considered and optimised in parallel with ergonomics parameters.

WP6: Implementation of skeletal IMMA
The objective of the work package was to implement the current version of the IMMA tool in the participating organisations, both universities and industry.

6 Results and its relation to objectives

This chapter presents the results of each work package. Each work package ends with a statement or a discussion where the results are set in relation to the objectives.

WP1: Project coordination and demonstrator development
The project was coordinated by the senior researchers Lars Hanson, Johan S Carlson and Dan Högberg. One kick off meeting, four larger project meetings (each 6 month) and a final meeting were arranged. These meetings were normally arranged at FCC and all partners were

invited. During these meetings, the research and developments were presented and discussed. The results were compared to the planned activities and a plan for next six months were presented, discussed and agreed upon. The academic partners, the larger aerospace and vehicle companies attended all meetings. The small partners were not able to attend all meetings. After each meeting, a report summarising the achievements was put together.

The demonstrator development was essential within the project, where the demonstrator supported communication, assessment and refinement of the tool. Hence, the demonstrator functioned as an important element of the research and development approach. Within the project, each partner, except one partner, carried out and presented one to three use cases. These use cases were used to feed the development of the tool and to confirm fulfilment of project objectives. At the final presentation meeting, a truck soil sump service task and an aeroplane assembly task in the wing were used to illustrate the new functions of the tool at lower TRL levels. Assembly of a centre console, a seat and an electronics unit were used to illustrate functions on a higher TRL level. Scientific journal and conference papers were published throughout the project. A list of publications is presented later in this report.

The objective to manage the project, develop demonstrators and publish papers is fulfilled.

WP2: Manikin dynamics and muscle model development

Traditionally, human simulation tools use quasi-static poses to emulate motion. This severely limits the possible set of motions which can be produced. Furthermore, the current version of the IMMA tool does not include muscle models, necessary to make assessments of work-related musculoskeletal disorders. The goal of this work package was to generate dynamically feasible motions for the manikin based on a performance index which could typically include quantities such as comfort, muscle strain and cycle time. Furthermore, we want to be able to realistically simulate highly dynamic motions, where modeling of inertial effects become crucial. To do this we model the manikin as a dynamical system, and use optimal control methods to compute the motions. Optimal control is the problem of determining a control function for a dynamical system in order to minimize a given performance index.

In order to solve the optimal control problem on a computer, we discretize the continuous problem into a nonlinear programming problem using discrete mechanics. In discrete mechanics, the variational principle is directly discretized into a set of nonlinear equations known as the discrete Euler-Lagrange equations. The discrete equations of motions, derived in this way, have been shown to be superior compared to standard discretizations since they preserve characteristics of the continuous system such as conservation of momentum and energy. This results in very stable integrators, which in practice allows us to use large time steps when solving our problems. In order to efficiently use the discrete equations, for these potentially high dimensional systems, in a direct optimal control method, it is important to exploit both the structure of the optimal control problem as well as the structure of the dynamics. This was accomplished by exploiting the partial separability of the discrete equations, and applying sparse finite differencing techniques.

By introducing dynamic simulation capabilities to the IMMA software, and adding muscles to the manikin, the aim of this work package was to take the digital human modelling tool to a new level, where not only loads on different joints in the body can be analysed, but where also musculoskeletal dose-response based evaluations can be made. This has been achieved using a Hill-type muscle model, simulating both active and passive components of muscle contraction, in combination with the framework for dynamic manikin simulations.

Muscle models were added to the shoulder, upper arm, forearm and around the wrist of the manikin to mimic the effect of real human muscles. For instance, the Brachialis muscle was added with its proximal attachment on the anterior of the humerus in the upper arm, and its distal attachment on ulna in the forearm. For the Barchialis muscle it suffices to simulate the shape of the muscle as a straight line between these origin and insertion points. For other muscles, specifically those extending over more than one joint, a model based on: origin - via point - insertion has been used.

Muscle activation was modelled as an activation signal – a value between 0 and 1 – very similar to the MVC (maximum voluntary contraction) concept used to assess muscular loads in work package 4. The activation signal is found by the optimal control optimization algorithm and gives rise to forces on the muscle attachment points, which are converted to joint torques that result in manikin motions. Each activation signal can control multiple muscles, allowing for simulation of broader muscles groups by having several single line segment muscles controlled by the same signal.

The fact that paths generated by the DHM tool are now dynamic, and have a time stamp for each manikin position, allows for extended comparisons between simulation results and measures made in the physical world, something we view as one of the great benefits added to the IMMA software from this work package. Output from the software now includes time dependent muscle activations and muscle forces, which can be used for instance when analysing the benefits and disadvantages of performing a task in alternative ways.

The IMMA manikin model was equipped with 35 muscles that act on the shoulder, upper arm, forearm and wrist. In total, each arm has close to 1000 muscle-related parameters controlling the strength of these muscles as a function of muscle activation, position of the arm, contraction velocity and maximum force. Future work would include research in automatized ways to tune these model parameters based on real world data and models, including the results from work package 4 of this project.

The objective to develop functionality to simulate manikin dynamics and to equip the manikin with muscle models is fulfilled. A demonstrator version on a mediate TRL-level (approx. 5) is available.

WP3: Methods for the consideration of human variation (strength and range-of-motion)

In the current version of IMMA, state of the art techniques for the consideration of anthropometric diversity have been implemented with a new interface that supports the work process currently used in industry but also supports more advanced analyses. However, the human-machine interaction is not only affected by the size and proportions of a user but also user capabilities, e.g. muscle strength and joint range of motion (ROM). The objective of the work package was to investigate which other parameters that are affecting human assembly work and how they can be considered in virtual simulations. The work was initiated through a literature study which concluded that there seem to be little correlation between body size, strength and ROM but also that there are few published studies where both body size, strength and ROM data have been measured and analysed at the same time. Due to the low correlation between and in-between different groups of variables, especially for ROM variables, the previously applied boundary case methodology was found unsuitable to use (Brolin et al. 2014). Instead another study was done where diversity in body size, strength and joint range of motion, together with diversity in other capability measurements, was included in the process of generating data for a group of test cases using cluster analysis (Brolin et al. 2016). This study also utilised a developed methodology for synthesizing population data by combining different sources to generate a complete database on an individual level. This cluster analysis technique was applied on synthesized data for body size, strength and joint range of motion to generate data for test manikins that were imported to IMMA and used in subsequent analyses.

The objective to develop methods for the consideration of human variation is fulfilled. Methods on a mediate TRL-level (approx. 5) for handling human diversity including body dimension, muscle strength and joint range of motions are developed and evaluated.

WP4: Assessment methods considering muscle activity
For assessment of muscle activity in the real world, electromyography (EMG) is typically used to record the electrical activity in the muscle. From the raw data the root-mean-square (RMS) values are usually computed as a measure of muscle activation level. To compare the muscle activation of different levels, the RMS values are normalized to the individuals' maximal voluntary electrical activation (MVE), which is the maximal RMS value obtain during maximal voluntary muscle contraction (MVC).

Arm muscle models were added to the manikin in work package 2. Similar to studies made on real humans, the IMMA software can compute the muscle activity level in %MVC. To describe the muscle activity over time, percentiles (e.g. 50^{th} and 90^{th} percentile of MVC) are often used. Today there are recommended risk limits for the forearm muscular load, which implies that work requiring > 30% of MVC during ≥10% of the workday, as well as work that requires > 10% of MVC during ≥ 50% of the workday, pose a risk for developing work-related muscular disorders. Likewise, insufficient muscular rest/recovery, i.e. if the muscular activity levels are < 0.5 %MVC less than 5% of the workday, that also constitute a risk for work-related muscular disorders in the forearm and shoulders. These recommendations are now used in IMMA for risk assessment of simulated upper limb muscle activity.

The IMMA software also allows analysing force and moment demands at each body joint of the IMMA manikin including compression and shear forces in the lumbar spine. This enables comparison to epidemiological peak load data regarding risk limits of spine force load (e.g. according to NIOSH maximum permissible limit suggestion for spinal compression) and population capabilities, e.g. for shoulder moment when performing a certain action. Hazardous loads and non-capable (for a relevant percentage of the population) actions thus may be identified at an early stage.

The objective to implement assessment methods considering muscle activity is fulfilled. Methods and limits for assessing muscle activity were found and implemented in the tool, on a mediate TRL-level (approx. 5). The functionality was illustrated at the final presentation, in two use cases at industry partners: the truck oil sump and aeroplane assembly tasks.

WP5: Ergonomics and productivity balancing
Ergonomics is defined as optimising human well-being and overall system performance. None or few virtual tools are concurrently focusing on both these parameters. Traditional digital human modelling tools available on the market are focusing on human well-being. On the market, virtual support tools for optimising system performance are available. Avix, developed by the Swedish company Solme AB, is one system optimising tool. Avix is used at the three big industrial partners in the project. Avix is used for balancing the production line based on time of tasks included. Within the work package, a first export and import function was developed between the IMMA demonstrator and Avix. An assembly sequence of tasks can be imported in the event editor that controls the manikin. The manikin performs the tasks and the IMMA demonstrator, using the ergonomics assessment module, adds an ergonomics score on each task. Sending this information of ergonomics scores and time back to Avix, it is

possible to balance the production line considering human well-being and system performance in parallel.

The objective to develop functionality for ergonomics and productivity balancing is fulfilled on a low TRL-level (approx. 4). Both the industry and the academic partners were aiming for a mediate TRL level when writing the project proposal. At one of the larger project meetings, in the beginning of the project, all partners agreed that the project should concentrate on activities related to the other work packages, and particularly on muscle simulation as this is the core of the project idea, and secure these deliveries. The main reason for this was the comprehension among the project partner representatives of the complexities to successfully optimise productivity and ergonomics at the same time, and the settlement that this large objective would benefit from being performed in a dedicated project rather than as a work package in this project.

WP6: Implementation of skeletal IMMA

Within this work package, the result from the SSF funded project Intelligently Moving Manikins (ProViking/PV09.13) was further developed. Updates were made in all modules of the software. The biomechanical model was improved to support both quasi-static and dynamic simulations, and to better represent the human skeleton. The shoulder model was updated to better represent the complexity of shoulders of real humans, and to offer better visualisations of the external skin model during shoulder movements. The number of segments in the hand was increased to be able to simulate a cupped hand. The spine model complexity was decreased to enable faster computations, but still keeping a good representation of the human spine. The placement of the spine was also refined to better represent real humans. The comfort function for controlling manikin motions was updated to make calculations faster. The comfort function considers joint limits, torque minimization and constraints such balance and view. The manikin automatically avoids collisions with itself and the environment. The anthropometric module has gone through a total makeover. The module includes functions for creating representative manikin families, supporting multiple anthropometric databases, free choice of anthropometric variables and PCA (principal component analysis) based methods to keep the number of manikins in families manageable. The appearance and the mesh of the manikin’s skin model was also updated. The tool include one female and one male manikin appearance. The language (instruction) editor developed in the IMMA project was converted to a general system for event handling, which now supports giving instructions to both humans and objects in the environment. The ergonomics assessment module was updated to partially include the German EAWS (ergonomics assessment worksheet) method, a recent ergonomics assessment method frequently used in Europe. Also Scania’s and Volvo’s company specific ergonomics evaluation methods were included in the assessment module.

The objective of the work package is fulfilled. The work done in the work package created an excellent basis for the development that followed, where the demonstrator was integrated in the IPS (Industrial Path Solutions) platform. This integration work was financially funded by CEVT, Scania, Volvo Cars and Volvo Trucks as a separate initiative.

7 Dissemination and publications

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	x	The dynamics simulation, the muscle modelling, personas for considering human

		diversity are three areas where new modelling techniques have been developed or where existing techniques have been introduced into new areas.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	x	Work package 6 created the basis for the IPS IMMA development project. The IPS IMMA project was financially funded by CEVT, Scania, Volvo Cars and Volvo Trucks. The first version of IPS IMMA was delivered to the Swedish automotive industry partners in October 2016. A tight cooperation between developers and users during the following six month will result in a first commercial version of IPS IMMA being available in April 2017.
Föras vidare till produktutvecklingsprojekt		
Förs vidare till forskningsprojekt		The Avix-IMMA demonstrator developed in work package 5 is the base for further development in the ITEA project NORMAN - Natural Simulation of Realistic Human Motions in Assembly Environments. The project proposal has passed the first gate and full application will be handed in 2017. The dynamic, muscle and personas demonstrator developed in work package 2, 3 and 4 is the base for further development in one work package in the VIVA – Virtual Vehicle Assembler project. The VIVA project application was submitted on 13 December 2016 to the Vinnova FFI Sustainable Production call.
Introduceras på marknaden	x	A commercial version of IPS IMMA will be available on the market in April 2017. The first version includes the basic digital human modelling functions. Muscles are not yet included. More research and further development is needed before adding muscles.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

7.1 Konowledge and result dissemination

Marketing events

	2013	2014	2015	2016
Applied Ergonomics and Human Factors Conference (AHFE)		2 papers Poland	1 paper US	
Triennial Congress of the IEA			2 papers Australia	

IEEE - Int conf on Automation Science and Engineering (CASE)				1 paper
International Symposium on Digital Human Modeling	2 papers and 3 posters US	4 papers Japan		
CIRP Conference On Assembly Technologies And Systems,		1 paper Germany		2 papers Sweden
Meeting arena for future successful workshops, Katrineholm	x	x	x	
ProViking day	Linköping			
Wingquist day, Gothenburg	x	x	x	x
Digital human modelling lectures	Skövde, KTH	Skövde, KTH	Skövde, Halmstad KTH	Skövde
ISO Symposium				Stockholm
European ergonomists annual meeting				Gothenburg
Innovation day, Skövde	x		x	

Follow-up projects

1. *Virtual Driver* (2015-2016). Partners: University of Skövde, Fraunhofer-Chalmers Centre (FCC), Volvo Technology AB, Scania CV AB, Volvo Cars AB. Total grant of 1471 000 SEK from the Knowledge Foundation (KK- stiftelsen). Grant 20140296.
2. *3D-SILVER* (2015-2017). Partners: GKN Aerospace, Combitech, Scania, ATS, Chalmers tekniska högskola, Fraunhofer-Chalmers Centre (FCC), University of Skövde. Total grant of 4 500 000 SEK from Produktion2030/Vinnova. Grant 2015-01451.
3. *Virtual Verification of Human-Robot Collaboration* (2016-2018). Partners: GKN Aerospace, Scania, ATS, Volvo Cars, Volvo GTO, Chalmers tekniska högskola, Fraunhofer-Chalmers Centre (FCC), University of Skövde. Total grant of 5 400 000 SEK from FFI Sustainable production/Vinnova. Grant 2015-03719.
4. *EMMA-CC - Ergo-dynamic Moving Manikin with Cognitive Control (2015-2018).* Internal Fraunhofer project with partners from Fraunhofer ITWM, Fraunhofer IPA, Fraunhofer IPK, Fraunhofer IAO and Fraunhofer-Chalmers Centre (FCC).
5. *Virtual Driver Ergonomics* – project proposal submitted to Knowledge Foundation.
6. *Virtual Ergonomics Assessment Process* – project proposal submitted to Knowledge Foundation.
7. *VIVA - Virtual Vehicle Assembler* – project proposal submitted to FFI Sustainable production/Vinnova.
8. NORMAN - Natural Simulation of Realistic Human Motions in Assembly Environments – project proposal submitted to ITEA Office.

Spin-off company

Virtual Ergonomics Sweden AB – Org number: *559070-4838* The company should develop, market and retail simulation and visualisation programs, software that provided the possibility to virtually verify products and workplaces from an ergonomic point of view. The company should offer education and perform consultant assignments within the area of digital human modelling. Furthermore, the company should develop other tools that offer proactively ergonomic work and other similar activities

Under the project software licences was sold the following companies.

Number	Company name	Number of licences
1	AB Volvo	4

2	CEVT	2
3	Scania CV	3
4	Volvo Cars	3

The one time licence cost was used to develop the software to a higher technology readiness level. The first commercial level will be available in April 2017.

7.2 Publications

PhD degrees and theses

1. Brolin, E. (2016) Anthropometric diversity and consideration of human capabilities: Methods for virtual product and production development, Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie, ISSN 0346-718X ; 4035
2. Keyvani, A. (2014) Structuring and use of motion data for computer manikin work task simulations Doktorsavhandlingar vid Chalmers tekniska högskola, ISSN 0346-718X; 3780

Master degrees and theses

1. Malin Idoffsson och Elma Basic (2016) Evaluation and Scania customisation of the Digital Human Modelling tool IMMA, Master thesis. KTH Royal Institute of Technology, Stockholm, Sweden
2. Victor Aguilar Pastor (2014) Digital manikin control through Microsoft Kinect, Master thesis, Universidad Miguel Hernández de Elche, Alicante, Spain
3. Luca Caltagirone, (2014) Human Interaction Solutions for Intuitive Motion Generation of a Virtual Manikin, Master thesis, Chalmers University of Technology, Gothenburg, Sweden

Bachelor degrees and theses

1. Susann Alsibai och Josefine Färjh (2014) Ergonomics simulation for the development and evaluation of health and safety on ships, Bachelor thesis, Malmö University, Malmö, Sweden

Journal articles

1. Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016). Development and Evaluation of an Anthropometric Module for Digital Human Modelling Systems. Submitted to International Journal of Industrial Ergonomics, Under review.
2. Högberg, D., Hanson, L., Bohlin, R. and Carlson, J.S. (2016). Creating and shaping the DHM tool IMMA for ergonomic product and production design. International Journal of Digital Human, Vol. 1, No. 2, pp.132-152.
3. Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016). Adaptive regression model for prediction of anthropometric data. Accepted for publication in International Journal of Human Factors Modelling and Simulation.
4. Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016). Adaptive regression model for synthesizing anthropometric population data. Submitted to International Journal of Industrial Ergonomics, Under review.
5. Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016). Generation and Evaluation of Distributed Cases by Clustering of Diverse Anthropometric Data. Accepted for publication in International Journal of Human Factors Modelling and Simulation.
6. Mårdberg, P., Carlson, J.S., Bohlin, R., Delfs, N., Gustafsson, S., Högberg, D. and Hanson, L. (2014). Using a Formal High-Level Language and Automated Manikin to Automatically Generate Assembly Instructions. International Journal of Human Factors Modelling and Simulation (IJHFMS), Vol. 4, No. 3/4, pp. 233-249.

Conference articles

1. Mårdberg, P., Yan, Y., Bohlin, R., Delfs, N., Gustafsson S. and Carlson J.S. (2016) Controller Hierarchies for Efficient Virtual Ergonomic Assessments of Manual Assembly Sequences, Procedia CIRP, 6th CIRP Conference on Assembly Technologies and Systems (CATS), 16-18 May, 2016. Volume 44, 2016, Pages 435–440.
2. Björkenstam, S., Delfs, N., Carlson, J.S., Bohlin, R. and Lennartson B. (2016) Enhancing Digital Human Motion Planning of Assembly Tasks Through Dynamics and Optimal Control. Procedia CIRP, 6th CIRP Conference on Assembly Technologies and Systems (CATS), 16-18 May, Volume 44, 2016, Pages 20–25.
3. Björkenstam, S., Carlson, J.S., Lennartson, B. (2015). Exploiting sparsity in the discrete mechanics and optimal control method with application to human motion planning. Proceedings of 2015 IEEE International Conference on Automation Science and Engineering (CASE), pp.769-774, 24-28 Aug. 2015 doi: 10.1109/CoASE.2015.7294174.
4. Blomé, M., Lundh, M., Hanson, L. and Högberg (2015) Introducing ergonomics visualisation and simulation for exploring design problems and solutions in workstation design on ships. Proceedings 19th Triennial Congress of the IEA, Melbourne 9-14 August 2015
5. Högberg, D., Brolin, E. and Hanson, L. (2015). Accommodation levels for ellipsoid versus cuboid defined boundary cases. Procedia Manufacturing, Volume 3, 2015, pp. 3702-3708,
6. Högberg, D., Brolin, E. and Hanson, L. (2015). Identification of redundant boundary cases. Proceedings of the 19th Triennial Congress of the International Ergonomics Association. Lindgaard, G. and Moore, D. (Eds.), Melbourne, Australia, 9-14 August, 2015.
7. Högberg, D., Brolin, E. and Hanson, L. (2014). Basic Method for Handling Trivariate Normal Distributions in Case Definition for Design and Human Simulation. Advances in Applied Digital Human Modeling. Duffy, V.G. (Ed.). AHFE Conference, pp. 27-40, ISBN 978-1-4951-2094-7.
8. Delfs, N., Bohlin, R., Gustafsson, S. and Carlson J.S. "Automatic Creation of Manikin Motions Affected by Cable Forces", Procedia CIRP 23, 35-40, 2014.
9. Bohlin, R. Delfs, N. Mårdberg, P. and Carlson J. S., (2014) A Framework for Combing Digital Human Simulations with Robots and Other Object, Proceeding of ISHS 2014, Third International Summit on Human Simulation, Tokyo, Japan.
10. Brolin, E., Högberg, L. and Hanson, L. (2014). Design of a Digital Human Modelling Module for Consideration of Anthropometric Diversity. Advances in Applied Digital Human Modeling. Duffy, V.G. (Ed.). AHFE Conference, pp. 114-120, ISBN 978-1-4951-2094-7.
11. Brolin, E., Hanson, L. and Högberg, D. (2014). Digital human arm models with variation in size, strength and range of motion. Proceedings of DHM 2014, Third International Digital Human Modeling Symposium, Japan, May 2014.
12. Hanson, L., Högberg, D., Carlson, J.S., Bohlin, R., Brolin, E., Delfs, N., Mårdberg, P., Gustafsson, S., Keyvani, A., Rhen, I-M. (2014). IMMA – Intelligently moving manikins in automotive applications. Proceeding of ISHS 2014, Third International Summit on Human Simulation, Japan, May 2014.
13. Delfs, N., Bohlin, R., Hanson, L., Högberg, D. and Carlson, J.S. (2013). Introducing Stability Of Forces To The Automatic Creation Of Digital Human Postures. Proceedings of DHM 2013, Second International Digital Human Modeling Symposium, USA, June 2013.
14. Brolin, E., Hanson, L., Högberg, D. and Örtengren, R. (2013). Conditional Regression Model for Prediction of Anthropometric Variables. Proceedings of DHM 2013, Second International Digital Human Modeling Symposium, USA, June 2013.
15. Keyvani, A., Högberg, D., Hanson, L., Lämkull, D., Delfs, N., Rhen, I.M. and Örtengren, R. (2013). Ergonomics risk assessment of a manikin's wrist movements – a test study in manual assembly. Proceedings of DHM 2013, Second International Digital Human Modeling Symposium, USA, June 2013
16. Mårdberg, P., Carlson, J.S., Bohlin, R., Delfs, N., Gustafsson, S., Keyvani, A. and Hanson, L. (2013). Introducing a Formal High-Level Language for Instructing Automated Manikins. Proceedings of DHM 2013, Second International Digital Human Modeling Symposium, USA, June 2013.

8 Conclusions and further research

In FFI's sustainable strategic roadmap, six main focus areas are mentioned: 1) *New products*, 2) *Competitiveness*, 3) *Environment*, 4) *Quality*, 5) *Lead time*, as well as 6) *Flexibility*. The project focused on research and development within the area of digital human modelling (DHM) in the context of digitalisation of product and production development processes, manual or semi-manual assembly and human well-being. DHM research and development is considered not to explicitly contribute to the focus areas *New products* and *Flexibility*. Still, the DHM demonstrator tool developed in the project will be realised as a new software product, offering flexibility in the sense that the tool can be applied to assist engineers in decision making in a large number of different design tasks and domains. To some extent the project contributes the focus area *Environment* by reducing the needs for building or modifying physical prototypes for verification of design proposals. The proposed project is however claimed to predominantly contribute to the three remaining focus areas: *Lead time*, *Quality* and *Competiveness*. These three focus areas highlight the need of using virtual tools to meet objectives. Within the competitiveness area, virtual tools for ergonomics simulation and workplace design is even explicitly mentioned. Fraunhofer-Chalmers Centre and Virtual Ergonomics Centre carry out research and development activities together with Swedish industry, which is the only work done within Sweden to close this gap. The result from work package 6 and the implementation project of developing and introducing IPS IMMA is the first basic delivery to the industry. The first basic version of IPS IMMA includes a bio-mechanical model including the skeleton, no dynamics or muscles are however yet implemented.

The demonstrator on muscle, dynamics and personas developed in the project needs more research and development before it can be implemented in the IPS IMMA digital human modelling tool. Furthermore, more research and development on reliable predictions of the time to perform specific motions is needed. In the current version of IPS IMMA, the appropriate times for the IMMA manikins to perform simulated tasks (e.g. assembly of components) are anticipated by the tool user. This manual input takes time and puts responsibility on the tool user, and adds subjectivity to the simulation and the following ergonomics evaluations. Another concern with the current version is that the two manikin appearances available in the tool always resembles a middle-aged male and female. This means that the manikins do not visually represent the diversity of people on the vehicle assembly lines, nor is successful of matching modelled physical properties of specific manikins (e.g. a 62 year old male). Having better matching appearances is alleged to improve the visual trust of the tool results.

The work introduced in the CROMM project to develop a virtual tool for the optimization of workers' well-being and overall system performance needs to be further investigated. Normally only one parameter is considered at the time, in separate tools, by one specific organization or expert. This results in a number of serial, and commonly iterative, activities for improving the production system. To reduce time and reach better solutions, there are needs for a software tool with easy access to both data driven and model based human motions that are able to optimize worker health and system performance in a faster and parallel process. The Swedish research agenda asks for such virtual tool able to optimise several parameters in a parallel process.

The work performed within this project had a vehicle manufacturing focus. Virtual tools for simulating humans is needed also in the context of vehicle design and development. Vehicle cockpit design (occupant packaging) is one such area, both applicable in traditional vehicle design where the driver's main task is to drive the vehicle, and in future vehicles where the driver's main task is to monitor the driving. Digital human modelling can also be used to verify passenger conditions, e.g. related to comfort, space, ingress/egress, vision and safety. In this project functionality for dynamics simulation was developed. This opens up the possibility also simulate vehicle situations where the consideration accelerations and inertia effects are important, for instance in extreme driving, accident and crash simulations. Within the project one partner was from the aerospace industry. IPS IMMA has been tested in pilot projects within the marine and health sectors where humans are interacting with products and workstations needed to be optimised for human well-being and system performance. The be really useful within these and other industry sectors there is need to perform more research and development.

9 Research parts and contact persons

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