THESIS PROPOSAL

HUMAN MOTION PREDICTIONS FOR AUTOMOTIVE ERGONOMICS DESIGN

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ABSTRACT

Studying how a product will affect the potential end-user is essential in product development (PD). In the PD process, such human-product interaction studies are typically addressed by ergonomics designer groups. Ergonomics designers use various tools to assess human well-being during the PD process, including physical prototypes, user tests and interviews, and human-product interaction simulations using digital human modelling (DHM) tools. DHM tools support ergonomics designers' work allowing for the assessment of product design relative to user requirements at early stages of the PD process when the product exists only as a virtual model. DHM tools have been widely used in the automotive industry for occupant packaging and interior design. However, these tools still present some limitations. One limitation is the ability of DHM tools to predict postures and motions with the desired accuracy. This limitation can significantly impact interior vehicle design, where current DHM tools typically require many manual adjustments from DHM tool users to get sufficiently accurate driving and passenger simulations. Manual adjustment processes can be time-consuming, tedious, and subjective, easily causing non-repeatable simulation results. Further, human motion predictions cannot be evaluated adequately due to the lack of driver and passenger ergonomics assessment methods that define what is acceptable for human-product interactions. Another issue is the usability of DHM tools themselves. Existing DHM tools may present complexities, lack reliability, or require a significant time investment. Because of these limitations, ergonomics designers must often run real-world validations of findings from DHM simulations, increasing the cost and time required for the vehicle development process. Thus, there is a need to develop new or improved methods for human posture and motion predictions, and enhance DHM tool usability for analysing ergonomics in the PD process. This research aims to advance DHM tools through the development of methods and models that increase the usability and accuracy of human motion simulations to support decision-making when addressing ergonomics in PD processes in the automotive industry. The expected scientific and industrial contributions of this research consist of developing methods and models that support human-vehicle interactions in virtual vehicle occupant packaging and interior design.

CONTENT

CHAPTER 1

INTRODUCTION

This introductory chapter describes the background of the research area of the thesis proposal. The aim and research questions of the thesis proposal are stated, derived from the identified needs. Expected contributions are also included.

1.1 BACKGROUND

Developing successful products generally requires complex design processes to meet customers' needs while meeting the product's industry, and governmental requirements. Product development (PD) is the set of activities required to create a clear and complete definition of a product (Mattson and Sorensen, 2020). Activities in a PD process require several areas, including mechanical engineering, electrical engineering, manufacturing engineering, industrial design, ergonomics, and user experience (UX) design. Identifying customers' needs and how a product will affect the end-user is a core activity in PD and an essential part of product design (Ulrich et al., 2020). Engineers and designers in charge of addressing, designing, and testing the human-product interaction typically perform such human-product interaction studies at relatively late stages of the PD process, even though there are benefits to proactively taking action regarding human-related aspects at earlier design process stages (Bernard et al., 2020; Schröppel et al., 2021).

One of the fields concerned with human-product interaction during PD is ergonomics. Ergonomics (or human factors) is the discipline concerned with understanding human interactions with other system elements to optimize human well-being and overall system performance (IEA, 2022a). Therefore, ergonomics designers are responsible for identifying and ensuring that human interaction needs are fulfilled during PD. Ergonomics designers can use various tools to assess ergonomics aspects during the PD process, including physical prototypes, user tests and interviews, and human-product interaction simulations using digital human modelling (DHM) tools. Most product design work is performed using computer-aided design (CAD) tools. DHM tools are an extension of CAD tools that incorporate human models into the digital design process for considering the interaction with the designed products providing crucial early insights to designers (Chaffin, 2005; Ahmed et al., 2021). DHM tools enable testing virtual humans, ensuring that product designs fit the users' requirements like health, comfort, safety, and ergonomics (Scataglini and Paul, 2019). However, DHM tools can be expensive, time-consuming, difficult to use, and subjective, making it hard to apply insights acquired to other aspects of the design process (Paul and Wischniewski, 2012; Ranger et al., 2018; Lämkull and Zdrodowski, 2020). Furthermore, development of DHM tools is required to do more advanced and accurate (closer to reality) simulations considering behavioural variability and human diversity (Wolf et al., 2020). Despite these challenges, DHM tools used in ergonomics design methods have been applied to many design contexts (Zhu et al., 2019). The ergonomics designers' objectives, workflow, and tools in these contexts may vary widely. This can make it difficult to identify ergonomics designers' challenges and what tools or tool improvements might enhance their ability to meaningfully contribute to the design process at early stages of PD.

Simulation software and DHM tools have been widely used in the automotive industry to analyse and improve vehicle occupant packaging (Gkikas, 2016). While DHM tools allow ergonomics designers to consider human aspects at the early stages of the design process, much of their work with DHM tools relies on their experience for predictions leading to non-repeatable and subjective results. Today's DHM tools still have limitations in considering human diversity and behaviour and lack methods to simulate, analyze, and evaluate vehicle ergonomics and user accommodation (Bhise, 2016; Brolin et al., 2020). Current posture and motion predictions in DHM tools have limited automation and accuracy, which means that manual adjustments are required from DHM users to get more accurate or realistic driving simulations (Jun et al., 2019). These manual adjustments generally consist of defining specific constraints over the acquired postures, which introduces an unspecified level of subjectivity and bias into the results (Chaffin, 2007). Those constraints may relate to the geometric features of the vehicle or the model of the human itself but can also be based on assumptions about human behaviour. The manual adjustment processes can be difficult, time-consuming, and subjective, easily causing non-repeatable simulation results. Often these predictions are "good enough" but do not necessarily reflect actual human movements (Lämkull and Zdrodowski, 2020; Demirel, Ahmed, and Duffy, 2021). Consequently, DHM tools constitute a good starting point for considering human aspects and product interactions, but the simulations require validations. Further, these predictions cannot be evaluated adequately due to the lack of standardized driver and passenger ergonomics assessment methods defining what is acceptable and what is not for human-product interactions in occupant packaging contexts. Additionally, DHM tools used in engineering design may be unstandardized, complicated to use, untrustworthy, or time-demanding systems (Paul and Wischniewski, 2012; Ranger et al., 2018; Lämkull and Zdrodowski, 2020). The development of new and/or improvements on existing methods and models of human motion predictions and DHM usability, in general, would allow for deeper insights into ergonomics earlier in the PD process with fewer real-world validations needed. Consequently, reductions in time-consuming validations would lead to time and cost savings in the PD process and possibly improved product design solutions as well. The improved simulation results could also be used as input for other departments or roles involved in the vehicle design process, such as vehicle safety that uses finite-element-based human body models (HBM) for virtual crash simulations.

1.2 AIM AND RESEARCH QUESTIONS

The presented problems indicate that current approaches cannot accurately and easily simulate human-product interactions. To address these issues, this thesis proposal *aims* to advance DHM tools through the development of methods and models that increase the usability and accuracy of human motion simulations to support decision-making when addressing ergonomics in PD processes in the automotive industry. Knowledge gaps related to the current workflow and ergonomic design challenges are addressed to identify further enhancement. Although different research questions must be answered to address various aspects of simulating human-product interaction gaps, they are contextualised and related by the following main research question that structures the entire work.

How can usability in decision support for human-product interaction simulations be improved to address ergonomics in product development processes?

The main research question is formulated to improve the usability and accuracy of ergonomic simulation studies to mitigate time-consuming procedures and simulation user bias. It is driven by efforts to facilitate the effective use of simulations and further establish accurate human-product interaction models for consistent and reliable ergonomic studies in automotive contexts. The stated main research question is divided into three specific research questions (RQ1-3): state of the art of DHM usage, simulation usability, and human motion prediction/modelling. The three specific research questions are oriented around at least one objective (O1-4).

RQ1 *State of the art of DHM tools usage.* How are DHM tools used for addressing ergonomics in automotive development processes?

- O1 Characterize the use of DHM tools for addressing ergonomics during the PD process in the automotive industry.

RQ2 *Simulation usability.* How can the usability of human-product interaction simulations be improved for providing decision support in the automotive development process?

- O2 Refinement and/or development of methods improving the usability of DHM simulations for analyzing human-product interaction in automotive ergonomics contexts.

O3 Validation of developed methods for improving the usability of DHM simulations with automotive ergonomics designers in the industry.

RQ3 *Human motion prediction models*. How can human motion predictions implemented in DHM tools be improved for automotive development processes?

O4 Consideration of human motion models in different research fields for improving understanding and developing models that increase human motion simulation accuracy in automotive ergonomics contexts.

As a first step, RQ1 aims to distinguish how ergonomics designers use DHM tools to address ergonomics in the PD process. Understanding ergonomics designers' objectives, current methods, and tools are essential for a holistic view of the PD process in the automotive industry. Further, the identification of their main challenges during PD constitutes research gaps and helps as directions for developing the present research. O1 supports RQ1.

Subsequently, RQ2 and RQ3 aim to investigate and develop potential solutions for improving the usability and accuracy of ergonomic simulations in the automotive context. This lack of usability and accuracy in DHM tools, which constitutes the research problem of this thesis, might not be a challenge that is caused by a lack of adequate tools. Instead, the issue could be attributed to missing or inadequate methods and models for simulations of human-product interaction in the ergonomics automotive context. Existing methods for simulating human-product interaction and how they are currently used in ergonomic simulation tools are reviewed to clarify needs and develop methods and models to enable more accurate human-product interaction studies in virtual PD processes while maintaining usability.

RQ2 considers current methods/procedures/practices for simulating driving tasks to determine how different possibilities, refinement or/and development of new methods can improve DHM tools' usability in the automotive ergonomics context. Describing *method(s)* as guidelines or procedures, that means, series of steps that help DHM users work systematically when digitally analysing human-product interactions. O2 and O3 supports RQ2.

Finally, RQ3 goes a step further into the human-product interaction modelling. RQ3 reviews how human interactions or motions are modelled in different research fields, first, for improving understanding, and second, for developing models improving accuracy in human motion simulations. Such developed models achieving improvements may take different forms. They may be improved by considering different or new variables, constraints, objectives, functions, or a combination of human motion prediction models from different research fields. In this sense, *models* refer to the mathematical representation of a system. In addition, validation will be necessary to prove its potential applicability to DHM tools. In this thesis, human motion prediction models consider human posture predictions since motions can be defined as a sequence of postures (Park et al., 2020). O4 supports RQ3.

The research context of this thesis proposal is virtual ergonomics and simulation, focussing on DHM tool usage within PD. However, results from other research fields, like cognitive science, are also considered in this research. This research should benefit designers, engineers, ergonomists, and product developers, as well as the research community, in the fields of design support tools for engineering and design, DHM, and human-product interaction.

1.3 EXPECTED CONTRIBUTION

This thesis proposal follows a Design Science approach to answer the presented research questions and accomplish the stated objectives. Unlike natural science, Design Science research aims to design, develop, and apply innovative artefacts to improve the understanding of a specific problem or to provide a solution (Hevner et al., 2004). Gregor and Hevner (2013) stated that design science contributions could be classified into various kinds depending on the application domain maturity and solution maturity. Following the classification from Gregor and Hevner (2013), the kind of scientific contribution of this research is: *Improvement*. Improvement in this context means knowledge contribution by the *development of new solutions for known problems*. The proposed research will focus on improvements to usability and accuracy. Besides, this research aims to achieve *explanatory and predictive knowledge* based on the knowledge types classification by Johannesson and Perjons (2014). Such classification describes the different purposes for which knowledge can be used. In this case, explanatory and predictive knowledge consists of predicting outcomes and understanding how the underlying mechanisms are related through causal relationships. The proposed research will enhance human-product interaction methods and models for simulation tools, particularly in automotive ergonomics contexts.

The expected contributions of this thesis proposal consist of achieving methods and models to improve simulation usability and accuracy of human-product interactions to support decision-making during the automotive development process. The expected scientific contribution of this research is understanding human-product interactions in occupant packaging contexts considering human diversity and variability. A further expected scientific contribution, not only for the DHM field but the human-product interaction field in general, is the development or improvement of models. The scientific contribution also constitutes knowledge development for industrial partners since all the developed knowledge regarding human interaction methods and models for simulation performance will benefit the PD process in terms of time and costs while contributing to sustainable development by reducing the number of physical prototypes needed in the PD process.

CHAPTER 2
FRAME OF REFERENCE

This chapter provides the context and theoretical background for the research field of this thesis proposal.

2.1 ERGONOMICS IN PRODUCT DEVELOPMENT

The significant movements within today's design world are technology-driven, sustainable, and human-centred design (Giacomin, 2014). Each is characterized by different core values and discourses based on technical novelty, planetary impact, or human meaning, resulting in notable differences in products, systems, or services (Giacomin, 2014; Ulrich et al., 2020). The transition to Industry 4.0 and the Information and Communication Technology (ICT) sector, where technology development drives many innovations, may involve missing the users' perspective (Steen, 2011; Nguyen Ngoc et al., 2022). The risk of such a technology-driven focus is that products or services are created so people cannot use or do not want to use them. That is why matching people's practices, needs, and preferences is a crucial factor in the success of innovations (van der Panne et al., 2003; van der Bijl-Brouwer and Dorst, 2017). Adopting one of these movements does not exclude the consideration of the others for the successful development of a product.

According to the International Organization for Standardization (ISO), human-centred design (HCD) is the approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system enforcing human factors, ergonomics, and usability knowledge and techniques (ISO 9241-11, 2018). A distinctive feature of human-centred design is that the natural focus of the activities, questions and insights lies on the people who intend to use the product rather than on the technological or material qualities of the product or the designer's creativity. As such, the entire design process is centred on designing to fit people's needs, preferences, and experiences during product interaction. To achieve this, it is essential to understand the different needs of individuals when interacting with a product so that human diversity and variability are adequately considered. Human diversity can include variation along many dimensions, including size, proportions, age, strength, cognitive abilities, experiences, cultures, and goals. Figure 1 illustrates human needs that may need to be identified and satisfied: physical, cognitive, and emotional.

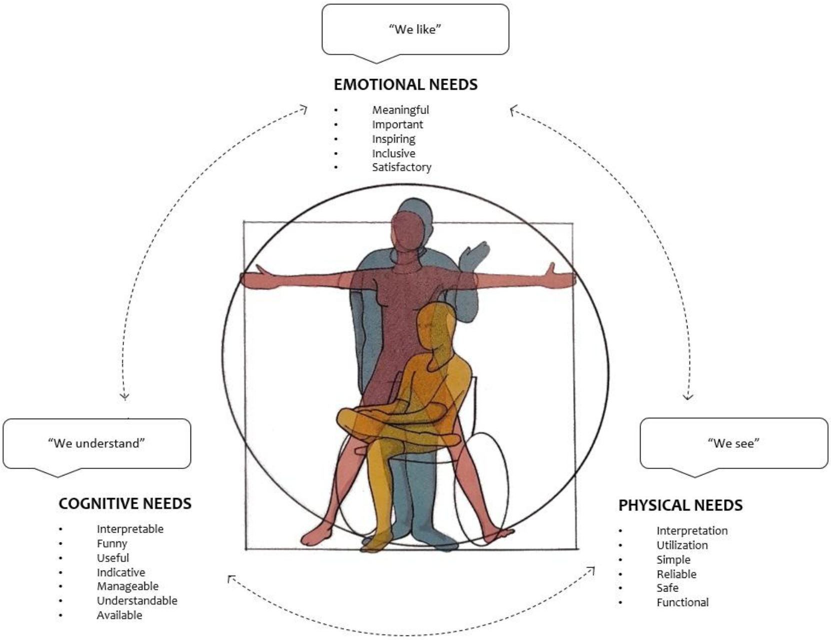

Figure 1. Human needs (Wikberg-Nilsson et al., 2021).

Physical needs relate to the proper function of the solution, e.g. the product functions safely and reliably. The cognitive needs relate to users knowing how to interact with and use the product, e.g. the product is easy to understand. And the emotional needs consist of developing meaningful solutions that contribute to the user's experience, e.g. a product that the users like (Wikberg-Nilsson et al., 2021). Human-centred design processes require collaboration among different design professionals, including ergonomists/human factors experts, user experience and usability specialists, and industrial or engineering designers, in order to develop products satisfying human needs.

Ergonomics is the scientific discipline concerned with understanding interactions among humans and other elements of a system, and the profession that applies theory, principles, methods and data in design to optimize human well-being and overall system performance (IEA, 2022a). Wilson (2000) explains the two aspects that the discipline of ergonomics should cover in more detail: (a) the theoretical understanding of all interactions in human-technology systems, and (b) the application of such understanding in design. As such, an understanding of purposive interaction between people and artefacts, (a), is the foundation of ergonomics. This understanding goes beyond describing interactions between a person, task, equipment, and environment to include an understanding of why behaviours unfold as they do and what factors can affect behaviours. To develop this understanding, ergonomists and practitioners often embrace scientific methodologies and approaches. The second aspect, (b), involves improving human interactions and conditions by applying the understanding of human behaviour to design interactions in real settings. Figure 2 describes different human interactions that may be analysed in ergonomics. In this model, the focus is on human-system interactions rather than the artefacts.

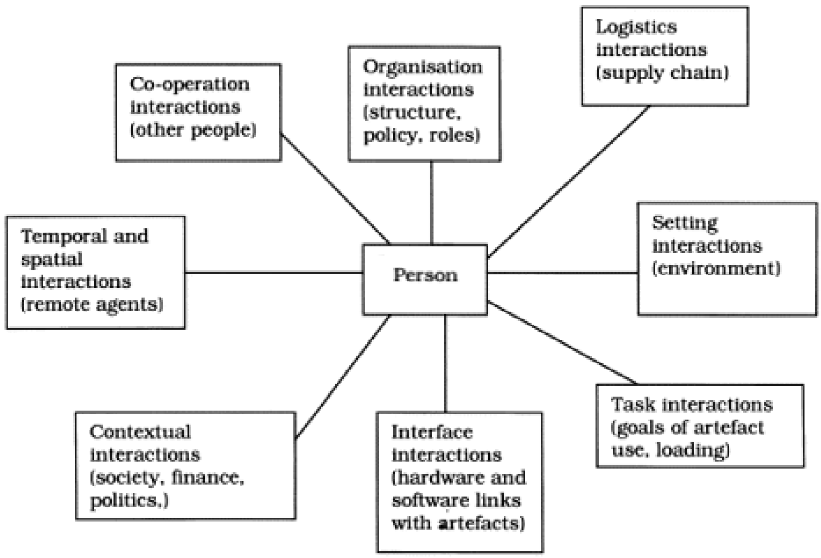

Figure 2. Human-system interactions in ergonomics (Wilson, 2000).

In short, ergonomics focuses on optimizing the interaction of humans with products and environments, following the principle of adapting the product or environment to human needs and conditions. In this case, a product may be a workplace, a task, a tool, equipment, or a job (Wilson, 2000). Ergonomics is a broad field involving several areas since it promotes a holistic approach and considers different relevant factors affecting human well-being. It can be divided into three fields or domains of specialization (IEA, 2022b):

- *Physical ergonomics* is concerned with anthropometric, physiological, and biomechanical characteristics.
- *Cognitive ergonomics* is concerned with mental processes and cognitive abilities such as motor response, memory, reasoning, and perception.
- *Organizational ergonomics* is concerned with improving sociotechnical aspects of the system, including organizational structures, processes, and policies.

Besides, usability is a term related to human-centred design and ergonomics. According to the International Organization for Standardization (ISO), the term *usability* means "the extent to which specified users can use a system, product or service to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO 9241-11, 2018). Usability is a more comprehensive concept than what is commonly understood as easy-to-use. Usability is relevant to regular ongoing use, infrequent use, learning, use by people with different capabilities, or maintenance. Accuracy, conversely, refers to the “closeness of agreement between a test result and the accepted reference value” (ISO 5725-1, 1994). This means the degree to which results of measurements, calculations, or simulations conform to the true or expected values. Accuracy encompasses the ability to obtain outputs that closely match the intended or desired values, ensuring a high level of correctness and fidelity in representing the characteristics or information being analysed. While usability and accuracy are not inherent attributes of a product or system, appropriate attributes and methodologies can contribute to a product being usable and accurate in a particular context (ISO 5725-1, 1994; ISO 9241-11, 2018).

Ergonomics designers can use various tools, with different degrees of usability and accuracy, to proactively assess ergonomics aspects at the early stages of PD, including physical prototypes, user tests and interviews, and human-product interaction simulations using digital human modelling (DHM) tools.

2.2 DIGITAL HUMAN MODELLING

DHM tools are meant to support human-product interaction or ergonomics aspects of design as soon as possible in the design process. They are particularly useful when the product exists only as a virtual model (Wolf et al., 2020). DHM tools are software systems that model the features and abilities of the human organism or its elements and provide these models for further simulation (Wischniewski, 2010). DHM provides digital representations, reducing physical prototypes' needs and corresponding development time and costs (Scataglini and Paul, 2019). DHM tools are distinct from other CAD tools. They include a digital human model (a.k.a. manikin, computer manikin, or avatar) interacting with a digital product model in a given digital environment. The development of use contexts early in the design of a product help to assess and reduce unhealthy or uncomfortable conditions due to product design features related to end-users. Using DHM tools early in the design process is commonly referred to as *proactive ergonomics* because it enables designers to run "what-if" scenarios in the early design phases (Ahmed et al., 2019). In such cases, DHM tools benefit design and manufacturing engineers by providing simulations, evaluations, and optimizations to support the design work and reduce redesigns late in product and production design processes. Waiting to identify and resolve ergonomic issues until after they arise in later stages of the PD can be referred to as *reactive ergonomics*.

Perhaps the most significant benefit of using DHM tools for assessing human-product interaction is their ability to represent the diversity of human anthropometry by enabling the creation and use of manikins of different sizes and proportions in simulations and evaluations. DHM tools allow the designer to avoid using an "average" person or, more likely, whoever is free in the next cubicle to assess ergonomics (Daniels, 1952; Holmes and Maeda, 2018). Using an "average" person is particularly problematic because the resulting design might be unsatisfactory for everyone who is too far from average, possibly resulting in a product that is aimed to be designed for everyone but fits no one (Daniels, 1952; Pheasant and Haslegrave, 2006).

Because the size and shape of human beings are infinitely variable, it is impossible to capture all the possible human variations. Thus, anthropometric models provide a realistic geometric representation of people with a wide range of anthropometries to evaluate ergonomics across a range of possible variations. DHM tools also allow individual body dimensions to be personalized, and some provide complete freedom to create customized human models. Customization of models is typically accomplished parametrically by providing specific measurement values or percentile data. Examples of DHM tools used in the industry which include customizable human models are Siemens Jack (Raschke and Cort, 2019), Virtual Ergonomics by Dassault Systemes (Charland, 2019), Ramsis by Human Solutions (Wirsching, 2019), Santos (Abdel-Malek et al., 2019), IPS IMMA (Hanson et al., 2019), and EMA (Bauer et al., 2019). Customizable models provide an intuitive opportunity to understand the interaction of a diverse group of individuals with a product, promoting inclusiveness. For example, families of manikins based on different population databases allow a designer to consider anthropometric diversity efficiently, reducing the risk for major design flaws that affect some users but not those most often considered (Brolin et al., 2019). The ability to test products and processes in digital simulations also avoids any potential risk that initial product testers could suffer, favouring safety and a sustainable work environment.

DHM tools can also be used to consider biomechanical aspects of humans for design assessments. Biomechanical human models offer a detailed representation of the musculoskeletal systems that enable static and dynamic human motion analyses. The calculation of these dynamic analyses includes internal stresses and joint forces. Such biomechanical analyses can be quantified and used as a metric for proactive ergonomic assessment and as an approach for enhancing the design decisions made by design engineers (Rasmussen and Christensen, 2005; Wagner et al., 2008). Examples of biomechanical DHM tools include AnyBody Modelling System (Damsgaard et al., 2006), OpenSim (Seth et al., 2018), and Santos (Abdel-Malek et al., 2019).

Another powerful feature of DHM tools is producing graphic representations of humans interacting with products and workstations. This feature helps designers identify and better understand and makes it easier to communicate to other people involved in PD the physical design issues relating to human-product interaction. There are different aspects of human-product interaction representations worth mentioning. The first aspect is that DHM tools offer different graphical representations of manikins interacting with the digital environment, from stick figures to more realistic appearances (Lämkull et al., 2007). A second aspect is the ability to show appearance diversity, i.e. the DHM tool's ability to represent different-looking manikins. Manikin appearances can be associated with data-driven personas or different personas' perspectives within the same level of realism (Kolbeinsson et al., 2021). Furthermore, a third aspect is the application environment, where the manikin interacting with the product can be viewed. Computer monitor presentations are the most widely used, followed by cave automatic virtual environments (CAVE), head-mounted displays (HMD), augmented reality technology, or a hybrid of them (Zhu et al., 2019). Each of these presentation formats has benefits and challenges. However, in all cases, the ability to represent design issues graphically benefits designers by providing a sharable representation of the product in the use context with a range of end-users. With a common representation, multiple stakeholders can work with a shared reference regarding the experience of a diverse group of users. The results can be more productive design meetings with fewer communication challenges. Thereby, there is no requirement that all stakeholders become experts in CAD, ergonomics, or DHM tools to be able to contribute to the design process based on their own knowledge, experience, and goals. Consequently, visualization is a feature of DHM tools that promotes and aids interdisciplinary teamwork (Lämkull et al., 2007).

Although the current DHM tools have clear benefits and potential, they are still limited. An axiom within virtual ergonomics and DHM is that "humans can be modelled and simulated," however, this is not entirely true because of the human motions and behaviour complexity. Most DHM tools focus on physical ergonomics and cover limited cognitive and perceptual aspects of human behaviour. Human emotion, mental workload, and decision-making variability have not been adequately included in current DHM tools (Duffy, 2012). Despite challenges in creating precise DHM simulations, a handful of expected action sequences or static postures can often guide the enhancement and assessment of specific ergonomic aspects. As such, DHM users typically specify only key manikin postures. Then, DHM tools can predict manikin transitions between these postures, often based on some definitions of ergonomic optimization (Zhu et al., 2019). Often these predictions are "good enough" but do not necessarily reflect any specific actual human movement.

When there is a need to analyze complex human postures and motions that DHM tools cannot simulate with sufficient accuracy, technology such as motion capture, virtual reality (VR), augmented reality (AR), or mixed reality (MR) can be integrated (Zhu et al., 2019). Examples of DHM tools able to use motion data captured from real humans are AnyBody Modelling System (Damsgaard et al., 2006), Siemens Jack (Raschke and Cort, 2019), EMA (Bauer et al., 2019), and IPS IMMA (Hanson et al., 2019). The main limitation of DHM-integrated motion capture is that although the recorded movement has a high level of accuracy, it is often difficult to align these movements and their consequences with digital geometries and use contexts (Qiu et al., 2014). Further, it is important to note that while recorded behaviour in DHM tools exhibits high accuracy, it primarily represents the individual being recorded. The extent to which this information can effectively represent other individuals, which is often required in design, needs to be carefully considered, especially when designing for a broader user base or catering to specific user groups with distinct characteristics. In addition, using these types of technology requires subject studies using a physical or digital prototype. While physical prototypes are of limited use for proactive assessment, digital prototypes still require human subjects with the corresponding time-consuming process and user test costs (Ahmed et al., 2019). Using technology systems such as motion capture/VR/AR/MR for human movement simulations used in the PD process involves limitations such as data failures, inaccuracy of the simulation result, or additional time-consuming procedures.

Further challenges are introduced because DHM tools do not currently consider, simulate, or analyze non-anthropometric or non-biomechanical aspects of users that may influence product interactions. These aspects can include understanding the impact of clothing or worn equipment on DHM simulations. Although DHM software like Ramsis and Santos have developed some functionality in this direction, it is still limited in most DHM applications. Manufacturing, military, and similar organizations are particularly interested in the effect of safety equipment on operators or body armour on soldiers, affecting the operator/soldier and how they interact with vehicles and additional equipment. Beyond clothing, DHM tools typically treat non-human items as solid non-deformable bodies. Thus, in automotive design, the effects of deformable materials used in seating are not fully simulated (Marshall and Summerskill, 2019). Such deformation can impact human-vehicle interactions, leading to unexpected issues related to visibility or reaching within the vehicle. These interactions can further challenge those working with DHM tools and anthropometric data in the design stages.

Another challenge involves integrating detailed biomechanical models into DHM tools. Despite the inclusion of simplified biomechanical models, most DHM tools lack comprehensive and detailed musculoskeletal models due to their computational complexity and high cost. This is further compounded for dynamic simulations of movement behaviours. For this reason, biomechanics evaluations with DHM tools are limited and typically focused on estimated instantaneous joint angles and torques. Even with good biomechanical models, additional challenges are introduced through motion control inaccuracies in simulations, increasing uncertainties of velocities and accelerations of digital human movements (Wagner et al., 2008). Further, the limited biomechanical models mean that other physical aspects relating to atypical constraints on the range of motion, forces, or other physical limitations are currently often not explicitly considered in DHM tools, which are noteworthy for designing sustainable and inclusive products.

Finally, while DHM tools can provide important insights into user-centred product design, many DHM tools have limited usability. According to various studies, some DHM tools in engineering design may be unstandardized (Paul and Wischniewski, 2012), complicated to use (Ranger et al., 2018), not trustworthy or time-demanding systems for the development of the study of human interactions (Bertilsson et al., 2010; Wischniewski, 2010; Perez and Neumann, 2015). By improving the usability of DHM tools, the accessibility of DHM tools for proactive ergonomic assessment would correspondingly improve (Högberg, 2009; Lämkull and Zdrodowski, 2020).

2.3 HUMAN MOTION PREDICTIONS

Specifying interaction models and inaccurate human motion predictions are long-standing challenges for DHM. Back in 1997, Broberg (1997) conducted a survey showing that the potential users of human simulation tools might not have sufficient ergonomic expertise to understand the predicted ergonomic outcomes provided by existing DHM tools. Further, the inability to predict human motions has been a driver of the development of the HUMOSIM Laboratory at the University of Michigan in 1998. Some years later, Chaffin (2007) outlined some significant issues to address for improving the human simulation functionality of DHM tools. He also highlighted the importance of having valid postures and motions available since the consequent ergonomic and biomechanical analysis can involve errors without them. Lämkull et al. (2009) compared DHM simulations showing the correctness of human predictions for simple tasks. In contrast, the experts' opinions were required to evaluate or modify the task in complex and asymmetric postures. Even though several authors have proposed different methods to solve, or at least improve human-product interactions (Wolf et al., 2020), it is still reported as a research trend and gap for future directions in recent years for DHM tools (Wischniewski, 2010; Zhu et al., 2019; Demirel et al., 2021; Hanson et al., 2021). That highlights the importance of the topic and its complexity.

Regarding current DHM tools, the lack of proper human posture and motion predictions is still present. Current simulations require DHM users' manual adjustment to obtain more accurate postures and motions. However, these manual adjustments may involve several issues (Lämkull and Zdrodowski, 2020).

- Inaccurate human postures occur when manikins have to perform tasks interacting with the boundary of reach motion geometries.
- The collision avoidance feature makes the manikin behave as if those particular geometries were "lethal to touch", which might be necessary for human interactions with harmful equipment, but it is not always the case.
- DHM users do not know the root cause of the awkward or inaccurate body postures, making it more challenging to adjust and define constraints to improve them.
- The procedure for generating human motions with task animation wizards is time-consuming. Often many sub-actions or sub-tasks must be created to make the movement of the manikin more accurate and less "robot-like".
- There is an uncertain bias involved in the results. Manual adjustments rely on DHM users' experience and subjectivity, varying among the ergonomics designers' teams.
- Need for validations. The uncertainty of simulation results needs to be validated with prototypes, user tests, or interviews to create good products.

It is worth highlighting the authenticity of DHM predictions and the associated graphics' importance for ergonomics analysis and evaluation. It allows designers to understand potential problems and risks better when humans interact with different designs (Chaffin, 2007; Zhu et al., 2019). In addition, while DHM tools also have limited usability for DHM users, it is worsened by inaccurate simulations and resulting adjustments.

DHM tools must include methods to predict human-product interactions to become a proactive digital tool (Chaffin, 2005; Wolf et al., 2019). While previous studies propose models with different perspectives and terminology related to human-product interaction systems (Chaffin, 2002; Högberg et al., 2019; Wartzack et al., 2019), all of them have in common the following four entities: the human/user/worker, the product/machine/workplace, the environment, and the task/interaction. Figure 3 represents the relation between these common entities across different models.

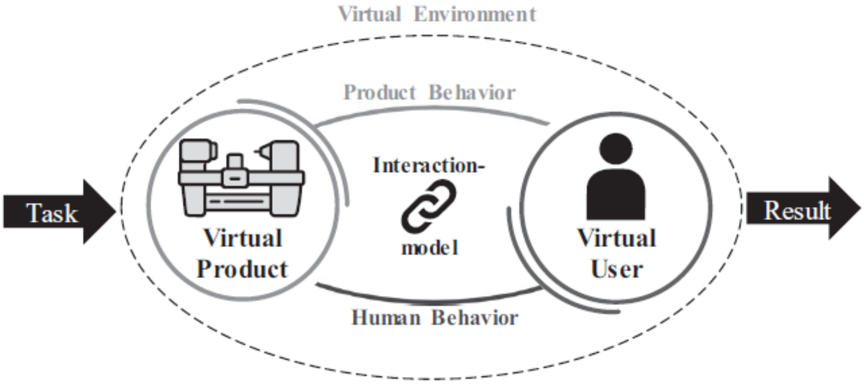

Figure 3. Virtual human-product interaction model (Wolf et al., 2020).

The human and product interaction works as a constant feedback loop. To properly evaluate the interaction, the prediction method should simulate the human motions accurately considering the entities above. Human motion prediction covers kinematic and dynamic aspects. Kinematics refers to the translational and rotational movement of points, bodies, and groups of bodies and the properties of the motion without considering what causes it, whereas dynamics refers to studying the causes of motion, the rules governing the motion (Pentland and Liu, 1999; Aristidou et al., 2018). Therefore, the methods to predict human motions in DHM tools may consider one or both aspects.

Human-product interactions include different forms, e.g., one may want to simulate the manikin touching, reaching, looking at, or seating in particular geometries/objects. DHM users simulate such interactions by defining target positions on geometries or products for specific body parts of the manikin to move to. However, this is the only information provided to the DHM tool, which means that the rest of the manikin body has to be simulated to behave like a real human. The manual definition of each body part of a manikin when interacting with any product would be a very time-consuming and tedious process. Moreover, if it were possible to accurately manually specify all aspects of human postures, that would imply that the predicted posture is already known, which is unlikely. The main idea behind proactive methods for human motion predictions is that few inputs can predict human motions accurately.

In essence, the presented problem in DHM tools simulations constitutes an Inverse Kinematic (IK) problem. An IK problem involves specifying the target of an end effector(s) as input and aims to calculate the pose of a biomechanical model (or articulated model more generally) such that the end effector can reach the target position and conduct the given task. The posture of the articulated model is the output of the problem. Ideally, a solution to an IK problem will provide an appropriate joint configuration of the remaining (uncontrolled) joints of the articulated model for which an end effector(s) moves to the desired target position(s) as accurately, smoothly, and rapidly as possible (Aristidou and Lasenby, 2011; Aristidou et al., 2018). End effectors are specific control points or joints of the articulated model, such as a human body, humanoid, or digital human model. Those control points can be either end joints such as hands or feet (typically referred to as end effectors), or inner joints such as knee or elbow. IK problems may have no, unique, or multiple solutions. However, many target positions will have infinite solutions for most chains with more than two degrees of freedom. The challenge of IK problems is identifying which from these multiple or infinite solutions is the correct one, i.e. the closest to a natural human motion. The definition of constraints, which are not always straightforward and known, is required to get closer to a natural human motion solution, selecting one solution from all the possible ones.

IK problems can be approached in different ways. Various motion modelling methods have been utilized over the years to predict how humans behave in terms of physical postures and movements. Several authors have attempted to categorize human posture and motion prediction approaches (Chaffin, 2005; Farahani et al., 2015; Wolf et al., 2020). While all the approaches aim to reduce the number of infinite solutions down to one, they follow different methodologies. These methods fall into the following groups: data-driven, optimisation-based, and inverse kinematics. The selection of solvers mainly depends on the definition and peculiarities of the problem. Desired smoothness, computational cost, scalability to different models, and the possibility to apply restrictions are several parameters to consider in selecting solvers or methods since they vary across the different types. These methods can be used for kinematic or dynamic human posture and/or motion predictions.

Data-driven (or phenomenological) methods predict human motions based on previously examined observations. A large amount of kinematic data from experiments is statistically analysed to get predictive models (correlation and regression models) of similar tasks to those captured (Farahani et al., 2015). This approach can also include reinforcement learning and artificial neural network methods. Data-driven methods solve the IK problem by allowing users to input key variables into regression or a trained model to predict the remaining joint values. The main advantage of this approach is the accurate or realistic appearing postures and motions. However, it needs considerable data to cover human anthropometrics and behavioural variability. Further, data-driven models are limited to predictions of cases that are similar to the data that the model is based on. Another limitation is the impossibility of analyzing individual differences between specific users, such as anthropometry or range of motion (Zhu et al., 2019; Wolf et al., 2020).

Optimization-based methods predict human motions using advanced optimization algorithms. Optimized variables may include kinematic or dynamic objective functions such as joint angle deviation, discomfort, and energy consumption to optimize human motion predictions (Yang et al., 2005). That means that optimization methods predict the remaining joint values of the IK problem by attempting to fulfil some set of optimization criteria. The main advantage of using this approach is that it provides accurate predictions of specific movements without previous observations of similar movements. Moreover, it also allows for analysis of the influence of specific additional dimensions, such as external forces or individual characteristics of humans and extra-kinematic/dynamic constraints. While these approaches can be more successful in novel cases than data-driven methods, they also introduce limiting assumptions that may or may not reflect actual human physical behaviour. These assumptions may include the duration of the movement, initial postures and motions, inaccurate optimizations, or constraint definitions. Further, predicting motions under objective functions can produce results that ignore human variability in favour of converging to an optimal solution. Also, the number of objective functions included can make it a highly iterative process with its corresponding computational time (Wartzack et al., 2019; Wolf et al., 2020).

Inverse kinematic methods predict human motions without using complex calculations. The IK algorithms are generally composed of simple operations involving points, distances, angles, and lines in an iterative fashion leading to an IK solution. IK methods can also handle the IK problem with several end effectors dividing the articulated model into smaller sub-sections and defining constraints to each joint independently rather than globally (Aristidou and Lasenby, 2011; Aristidou et al., 2018). The main advantages are the low computational cost of providing the solution very smoothly and quickly, and their easy implementation and broad applicability to different problems. However, one of their main limitations is the possible inaccurate motions occurring even with all the joint constraints fulfilled. So even obtaining a solution among infinite within the defined constraints could be inaccurate. Another limitation is integrating global constraints meeting spatiotemporal correlations with nearby joints. Cyclic coordinate descent (CCD) and forward and backward reaching IK (FABRIK) are two of the most popular IK solvers. Figure 4 exemplifies a complete iteration with a single effector of the FABRIK solution.

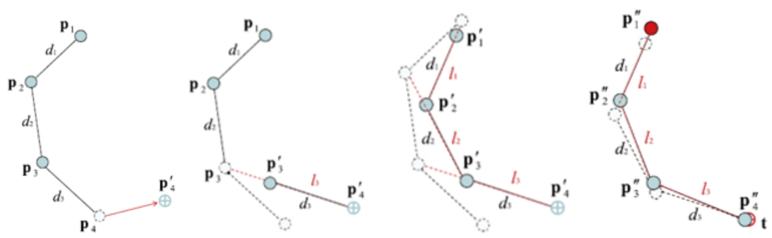

Figure 4. Complete iteration of FABRIK solver (Aristidou and Lasenby, 2011). p_4 is the end effector, t the target position, and p_1 is the root or initial position.

The previously mentioned methods can also be combined for human motion predictions.

According to Wolf et al. (2020), a suitable interaction model for engineering design should cover the following requirements:

1. A proactive/predictive approach requiring little to no previous knowledge or ergonomic expertise.
2. A universally valid approach, which is applicable to the majority of products and use cases.
3. A time-efficient, standardized, and intuitive modelling procedure.
4. A comprehensive and straightforward modelling approach.
5. Integration between CAE and DHM tools.

However, they also state that no human-product interaction model completely fulfils these criteria in current DHM tools. While data-driven and optimization-based methods are currently used in DHM tools, recent IK methods, such as the FABRIK solver, have not been implemented in DHM tools (Wolf et al., 2020; Demirel et al., 2021). IK may constitute a potential method for the defined IK problem in DHM tools. Further research is required to identify and characterise critical constraints affecting specific cases/tasks, such as the seated driving posture and motions as well as the critical constraints' suitability in the different human motion prediction methods.

2.3.1 PREDICTIONS OF SEATED DRIVING POSTURE

When considering occupant packaging or interior vehicle ergonomics in the automotive development process, it is essential to accurately predict the initial static posture of drivers and passengers. Getting this initial posture right is crucial because the design and development of other ergonomic requirements, such as seated posture comfort, operating controls, and interior and exterior visibility, depend on it. Different seated driving posture models have been developed through both data-driven and optimization methods of human motion prediction.

Data-driven or statistical regression models predict the coordinates or body joint angles of specific positions of humans in the car interior. These regression models consider different parameters from humans such as sex, anthropometry, age, or body symmetry, and vehicles such as vehicle class, seat designs, or driving venues (Reed et al., 2002; Park et al., 2016a). While these models share the same prediction approach, the data collection and analysis methodology varies and is not always adequately described (Schmidt et al., 2014). Other limitations are the prediction of individualities and the difficulty of developing regression models considering all human and vehicle parameters affecting the seated driving posture to cover human and vehicle variability.

Optimization processes aim to minimize expected discomfort by decreasing the deviations from neutral or optimum comfort angles. The main limitation of this approach is that the models do not currently include individual-specific comfort joint angles based on anthropometry variables (Brolin et al., 2020). Furthermore, the lack of proper driver ergonomic evaluation methods, considering different postures for different body dimensions and postural variability, limits the application of this approach, especially because several distinct objective functions likely affect driving posture predictions.

To summarize, the lack of accurate seated posture predictions means that DHM users typically rely on their experience to refine postures so that they are more accurate and closer to reality. Ergonomics designers validate DHM tools results following SAE standards (Bhise, 2016).

2.3.2 HUMAN MOTION PREDICTION IN OTHER FIELDS

Human motion prediction receives significant attention across a range of research fields beyond automotive ergonomics design. Understanding and modelling human motions has garnered the interest of researchers from different disciplines, including psychology and cognitive science (Mohamed, 2015). Research from other research fields targeting human motion analysis and prediction can provide a deeper understanding of human motion while providing knowledge about new methods and models for improving human motion simulations within DHM tools.

In cognitive science, researchers have recognized the significance of predicting human motion for a wide range of applications. They have sought to understand the underlying cognitive processes and decision-making mechanisms that drive human motion (Fajen and Warren, 2003). By developing models that simulate human behaviour, these fields aim to enhance the predictive capabilities of human motion simulations.

One example of a dynamic model used in cognitive science is the Time-to-Collision (TTC) model proposed by Lee (1976). The TTC model considers information about the relative motion of objects to estimate the time remaining before a potential collision occurs. By incorporating this model into human motion prediction, researchers have been able to anticipate human reactions and movements in critical situations, contributing to safer designs and interventions (Lee, 1976; Kiefer et al., 2006). Furthermore, the Steering Dynamics Model (SDM) has been a subject of interest within cognitive science. The SDM demonstrates how one can steer towards desired locations avoiding obstacles (Fajen and Warren, 2003). The authors of these models believe there is a need to integrate dynamical and information-based approaches for more complex, adaptive behaviour depending on interactions with the environment while following inverse kinematics algorithms. However, it is important to note that the SDM has primarily been developed in a two-dimensional (2D) space context, limiting its applicability in complex real-world scenarios.

Despite the advancements in these fields, their potential contributions to DHM tools and automotive ergonomics contexts are yet to be realized. By considering the diverse range of studies conducted in cognitive science, which delve into human decision-making, perception, and motor control, the capabilities of DHM tools can be enriched. Integrating and developing existing models and knowledge into DHM tools has the potential to improve understanding and accuracy while accounting for human behavioural diversity, ultimately enhancing automotive ergonomics design.

CHAPTER 3
RESEARCH APPROACH

This chapter presents the research approach applied to achieve the aim and answer the research questions of this thesis proposal.

3.1 PHILOSOPHICAL PARADIGM

Scientific research can be considered and conducted through different research paradigms. These research paradigms are the philosophies of science that guide the way science is conducted, and knowledge is created. Understanding the assumptions and principles of research paradigms helps clarify the findings and identify the gaps. The core elements of research paradigms are ontology (how reality is viewed), epistemology (how the knowledge is conceived), axiology (the role and values of the research process), methodology (processes associated with science), and rigour (the criteria used to justify the quality of research). There are several paradigms or ways of conducting research: positivism, pragmatism, interpretivism, or constructivism. Each paradigm has a different perspective on the core elements (Kaushik and Walsh, 2019; Oates, 2006; Park et al., 2020).

Because the completion of the presented research is developing an artefact(s), a tangible or intangible creation addressing a practical problem, this thesis proposal follows the Design Science approach. Many designers associate Design Science with positivism, although it could be conducted under different research paradigms, including pragmatism (Oates, 2006; Johannesson and Perjons, 2014). This thesis proposal follows the pragmatism research paradigm. Pragmatism is a research paradigm that focuses on finding practical solutions to problems by emphasizing the importance of context and experience. It emerged in the late 19th century in the United States as a response to the shortcomings of traditional philosophical and scientific methods (Tashakkori and Teddlie, 2003). Several factors, including the presented research questions (section 1.2), the context of the study, and the research methods, were considered for selecting the pragmatism research paradigm. This thesis proposal focuses on developing practical solutions to improve human interaction simulation methods and models used in the automotive industry, aligning with the pragmatism paradigm's emphasis on practical problem-solving. Further, this thesis proposal's recognition of the importance of context and experience also aligns with the pragmatism paradigm. The presented thesis proposal acknowledges that simulations of human-product interactions in the automotive industry constitute a research gap and that solutions must be tailored to the particular context in which they are applied. The pragmatism paradigm recognizes that knowledge is shaped by context and that solutions to practical problems must take this into account. An interdisciplinary approach in this thesis proposal, which also considers methods and models from different research disciplines, is also a strength of the pragmatism paradigm, as it allows for a comprehensive exploration of complex problems (Goldkuhl, 2012; Kaushik and Walsh, 2019).

Concerning the use of research methods, pragmatism is a paradigm that claims to cover the gap between scientific and naturalistic methods and newer approaches (Park et al., 2020). It involves using the philosophical and methodological approach that works best for the research problem being investigated, which means using mixed methods (Kaushik and Walsh, 2019). This constitutes another reason for adopting pragmatism as a research paradigm, i.e. the possibility of choosing different research methods according to the problem. Simulations and experiments are conducted to create knowledge and develop the artefact. In addition, various data collection methods, such as interviews, are also considered. While these different research strategies and methods underlie different research paradigms, pragmatism allows researchers to choose the best for the particular investigated problem.

3.2 RESEARCH STRATEGY AND METHODS

The research approach adopted in this thesis proposal is Design Science. Design Science has its roots in engineering and the science of the artificial (Simon, 1996). In contrast to natural science, which aims to explain how and why things are, Design Science is concerned with producing artefacts to attain goals or solve practical problems, and the knowledge about it and its effects on the environment. Natural science involves discovery and justification, whereas design science involves building and evaluating artefacts (March and Smith, 1995). Such artefacts are potential constructs, models, methods, or instantiations and may vary from software, physical objects, or combinations of both. Artefacts may consist of developing an entirely new artefact or improving an existing one (Hevner et al., 2004). In short, Design Science is the scientific study and creation of artefacts as people develop and use them to solve practical problems of general interest (Johannesson and Perjons, 2014). The addressed problem in this thesis proposal, as defined in Chapter 1, is the lack of reliable and consistent methods and models simulating human-product interactions considering human variability in occupant packaging contexts.

Peffers et al. (2007) define three crucial elements to develop Design Science research: *conceptual principles*, which involve a rigorous process to design artefacts; *practice rules*, which ensure that the artefact is created to address a problem, that it has utility; and a *process,* the different steps for carrying out and presenting the research. Besides, Design Science may seem similar to Design since both aim to develop artefacts based on previous ones. However, Design Science researchers aim to produce both a novel artefact and knowledge about it and its effects on the environment that is of general interest. In contrast, designers can create solutions that only satisfy a single actor. The difference between Design Science and Design gives rise to three requirements for Design Science research, which are aligned with the three crucial elements from Peffers et al. (2007):

1. Creating new knowledge of general interest requires the use of rigorous research methods.
2. The generated knowledge must be based on existing knowledge to ensure the originality and well-foundation of the proposed results.
3. The proposed new results should be communicated to both practitioners and researchers.

This thesis proposal considers and follows the three mentioned requirements as a base to develop Design Science research properly. Following the stated descriptions, this thesis proposal fulfils the three conditions as follows:

1. This research aims to improve the methods and models that the automotive industry uses during the PD process. This research is developed in close collaboration with several Swedish automotive companies. That means that different sources and stakeholders are considered in developing the artefact. Consequently, the results will be generalized to all of them while maintaining rigour by choosing the appropriate strategies and methods during the different stages of Design Science.
2. This research is creating artefacts, methods and models, that improve a practical problem based on the knowledge of previous research projects and in close collaboration with industrial partners. Literature review considering different fields and close collaboration with industrial partners leads to identifying and approaching state of the art gaps and used methodologies. The relation of this thesis proposal to previous knowledge and current practices makes it possible to assess the proposed results correctly.
3. This research's scientific results are communicated to researchers and industrial professionals through publications in conferences and journals, as well as through industrial presentations and similar events.

The Design Science approach encompasses a variety of research strategies and methods. Research strategy refers to the overall approach or plan of action to answer the research questions; it is concerned with the big picture of the research project. Research methods, on the other hand, refers to the specific practices and techniques applied to address the research questions and objectives (Jr et al., 1990). Based on the research context, questions and objectives, simulations and experiments are the strategies to address the stated research questions.

Simulations use computer software to model "real-world" processes, systems, or events (Law and Kelton, 1991). Simulation involves representing the underlying theoretical logic that links constructs with simplified worlds (Davis et al., 2007). In this case, simulation is one of the strategies to study and develop improved methods and models of human-product interactions. Experiments investigate cause-and-effect relationships, test hypotheses, and seek to prove or disprove a causal link between a factor and an observed outcome (Oates, 2006).

Experiments are used to study and identify critical variables of human-product interactions in occupant packaging contexts. Visibility, reachability, clearance or roominess, and driving posture are relevant aspects analysed through experiments.

DATA COLLECTION METHODS

Different data collection methods are employed to conduct this research during the Design Science process stages. Documents and interviews were used in the initial stage of problem identification and definition of requirements. Documents, observation, interview/questionnaires, fieldwork, and motion capture data are data generation methods considered during the subsequent phases of the Design Science process, design and development, demonstration, and evaluation.

Documents such as papers, white papers, standards, and books are analysed to extract useful information for the research. Documents include multimedia documents, such as videos, diagrams, pictures, etc. In addition, researcher-generated documents are also part of the research.

Interviews are a particular kind of conversation generally led by a researcher covering a specific topic of interest to generate material for research purposes. Interviews can be divided into three different types: structured, semi-structured, and unstructured interviews (Oates, 2006). Interviews were used at the initial stages since they allowed the researcher to obtain detailed information from experts about state of the art experiences, working methods, needs, and issues. That helped identify the gaps and real problems and, consequently, served as a base to define the requirements and objectives of the project. During the later stages of the research, interviews/questionnaires are also considered a data collection method to capture the ergonomics designers' view and demonstrate and evaluate the developed artefacts.

Observations consist of watching and paying attention to what people do rather than what they report they do (Oates, 2006). Observations is another data collection method considered mainly during simulations and experiments in the design and development stage. Observation methods contribute to understanding and identifying critical aspects of human-product interactions in occupant packaging.

Motion capture consists of recording the movement of people or objects. The data is obtained by systems that measure the positions and orientations of objects and bodies. Motion capture allows the collection of accurate, objective, high-volume observational data to augment traditional observation methods.

Fieldwork or field research is a qualitative method that aims to observe, interact and understand people while they are in a natural environment. Continuous meetings, workshops, and demos with associate companies constitute the environments of interest. Fieldwork is used throughout the development of this research to understand the needs and critical challenges of industry partners for developing this research.

DATA ANALYSIS METHODS

Qualitative and quantitative analyses are employed during the development of this research. The qualitative methods involve transcriptions from interviews, fieldwork and meeting notes, and non-textual data like pictures or diagrams. The qualitative data obtained in the initial stages of this research was analysed meticulously to gain insights into the automotive ergonomics goals, workflow, and tools, and to identify their fundamental needs and limitations.

Quantitative data analysis methods include statistical analysis and visual aids such as diagrams, charts, or graphs. Central and distribution tendency and correlation tests are the statistical analyses considered for the quantitative data obtained during simulations and experiment to determine the significant relationship between variables in driving postures and tasks.

3.3 RESEARCH PROCESS

Several researchers have proposed different frameworks to help researchers conduct Design Science research effectively. Hevner et al. (2004) identify seven guidelines that form the fundamental principles researchers should uphold in some manner to complete Design Science research. Fischer and Gregor (2011) introduce a Design Science framework based on the scientific method arguing that both are similar in several aspects. This thesis proposal follows the Design Science research process proposed by Peffers et al. (2007) and Johannesson and Perjons (2014). These authors define five different steps within the Design Science approach: 1) Problem identification; 2) Definition of requirements and objectives; 3) Design and development; 4) Demonstration; and 5) Evaluation.

Knowledge gained during the process's design and development, demonstration, and evaluation phases is iteratively fed into the research process to ensure the rigour of the artefact and its internal validation. Every step of the research process contributes to answering this thesis proposal's research questions and objectives. Figure 5 illustrates the different research strategies, data collection, and analysis methods in each phase of the adopted design science process.

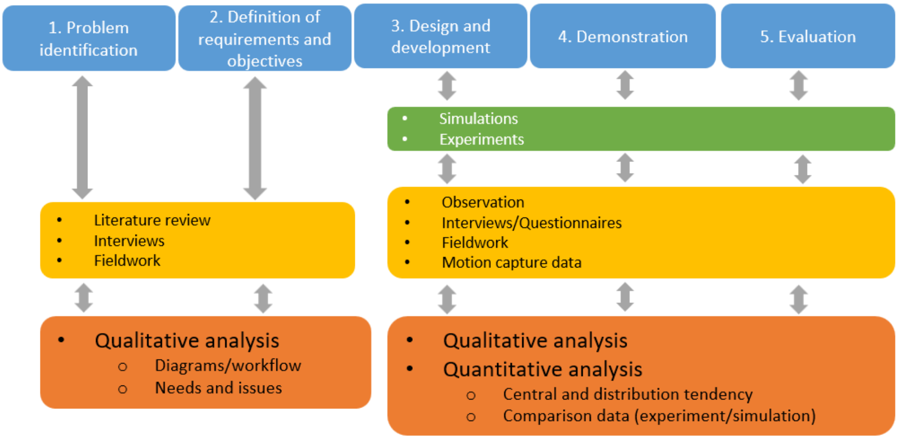

Figure 5. Research process.

3.4 ARTEFACT'S VALIDITY

The artefacts developed in this research, methods for improving usability and models for enhancing the accuracy of simulations, will be evaluated in two different ways. On the one hand, when it comes to the methods' validation, the validation will be done by comparing the DHM tool performance as it was before the developed methods in this research with the DHM tool performance with the developed methods in this research. This means comparing today's simulation tools' functionalities with the developed methods for improved usability performance in simulation tools for automotive ergonomics design. Several industrial partners will be involved in making such a comparison. Getting several evaluations from different companies helps generalize the results and ensure that the artefact can be applied to solve problems for different users or types of vehicles. Comparisons may be evaluated with usability surveys of DHM users, including effectiveness, efficiency and satisfaction metrics. Additional company feedback can complement the satisfaction surveys to indicate possible side effects of the developed artefact. O3 of this thesis proposal covers the evaluation of the developed methods.

On the other hand, the developed models for improving the accuracy of human-product interactions will be evaluated by comparing them to data collected in experiments of occupant packaging contexts. In this way, the simulation results from the models will be assessed against the motion capture data. Analysis of the measures obtained from both methods, simulations and data collected from experiments, such as body joint angles, visibility angles, collision distances, path planning position and orientation, or motion velocity, will define the accuracy of the developed models. These evaluations will be done iteratively during this research's development to improve the artefact's effectiveness and validity.

3.5 ETHICAL CONSIDERATIONS

The research area of virtual ergonomics includes both social and applied science, which means that human subjects are directly involved in this research. The different stages in which the research should analyze and consider ethical concerns are:

- Data collection from interviews or motion capture systems (informed consent, privacy, and safety)
- Making predictions based on the data collection (with a possible lack of accuracy)
- Producing simulations (based on human behaviour predictions)

While this research aims to improve the accuracy of human motion predictions, not all the possible factors affecting human-vehicle interactions will be considered. Awareness of this shortcoming is important because all possible motions might not be included and considered in the simulation and artefact development. Some atypical or outlying behaviours (and people) could be excluded. To ensure the quality of the research and its development, at these three different stages, the research ethics code provided by the Human Factors and Ergonomics Association (Code of Ethics HFES, 2020), the protection of individual rights (consent), data management, the risk of bias or poor judgment, and research misconduct issues are considered.

CHAPTER 4
PRELIMINARY RESULTS

This chapter summarises the papers associated with this thesis proposal and the progress made so far.

4.1 PAPER I

Perez Luque, E., Brolin, E., Högberg, D., Lamb, M., 2022. Challenges for the Consideration of Ergonomics in Product Development in the Swedish Automotive Industry – An Interview Study. Proc. Des. Soc. 2, 2165–2174. https://doi.org/10.1017/pds.2022.219

The study reported in Paper I aimed to provide an understanding of the state of the art of how ergonomics designers work in vehicle design within the Swedish automotive industry. A corresponding objective was to identify how methods and tools, such as DHM software, support the ergonomics designers' work and what improvements are desired for enhancing it. This was done through a semi-structured interview study including ten ergonomics designers from seven Swedish automotive companies working in PD. Interviews are a suitable data generation method for obtaining detailed information, asking complex questions, and exploring feelings and experiences that cannot be easily observed (Oates, 2006). Semi-structured interviews contain a list of themes and questions to be covered while offering flexibility for changes in the order and including additional questions if the flow of the conversation requires so (Ahmed, 2007). All participants involved in the study are considered experts following Littig's (2009) criteria since each had specialized knowledge in the specific domain of ergonomics PD/user-centred PD. Questions during the interview covered goals and objectives, workflow, tools, the main challenges in their work performance, and views on what would constitute an ideal tool.

Results show that the involved companies follow their own design methods when addressing ergonomics in PD. The most reported tools were physical prototypes, VR, and DHM tools for studying and analyzing the ergonomics aspects of a vehicle. The reported challenges were divided into interdepartmental communication issues and tool development issues that affect the workflow of ergonomics design in PD. Regarding what would constitute an ideal tool for working in the PD process, ergonomics designers include easy-to-use and consideration of anthropometry as essential feature. The paper identifies four main gaps and research directions that can address the current challenges that ergonomics designers face: human behaviour predictions, simulation tool usability, ergonomics evaluations, and integration between systems.

4.2 PAPER II

Perez Luque, E., Brolin, E., Lamb, M., Högberg, D., 2022. Simulation of hip joint location for occupant packaging design. Proc. 7th Int. Digit. Hum. Model. Symp. DHM 2022 Iowa Virtual Hum. Summit 2022 7. https://doi.org/10.17077/dhm.31742

Paper II focused on human posture predictions and the usability of DHM tools in the automotive design context. Accurately characterizing seated posture is crucial for ergonomic and safety design and evaluations. However, current predictions are not accurate enough, generally leading to time-consuming and subjective manual adjustment processes, also causing non-repeatable simulation results. The core limitation refers to the lack of a standardized connection between occupant packaging guidelines and the biomechanical knowledge of humans and their diversity. This study describes the relationship (or lack of it) between one of the key reference points used by vehicle designers (H-point) and human kinematic models used in DHM tools (mid-hip). The H-point describes a theoretical intersection of a reference occupant's torso and thigh lines (Gkikas, 2016). This means that the H-point simulates but does not precisely represent the human mid-hip joint location and its variability across people. Paper II presents an approach to sit manikins in a virtual environment considering geometric reference points and human body shape.

Looking at the literature, many authors have investigated human body angles in driving situations to determine expected driving postures. However, the results of these studies are typically not specified in terms of actual vehicle reference points, making it difficult or impossible to apply the results in current design contexts without significant effort. Park et al. (2016b) developed a data-based prediction model for drivers considering body dimensions, age, and gender from humans concerning vehicle layout measurements. However, the Statistical Prediction approach proposed by Park et al. (2016b) exhibited some issues in certain cases (Brolin et al., 2012). Regarding how seated driving posture is currently addressed in practical use, DHM tools mostly follow the same procedure for adopting the initial seated driving posture, a DHM standard procedure. This procedure, identified in workshop discussions with automotive companies, consists of the following steps: 1) the manikin family assumes a default driving posture, generally defined by the DHM software following specific angles according to a particular study; 2) constraints are set to fulfil basic requirements such as feet on the pedals and grip points on the steering wheel; 3) finally, manual adjustments, typically in the mid-hip and/or torso, are often made to get the manikin postures fitting the seat. This DHM standard procedure is limited by not defining the relationship between the mid-hip (manikin) and the H-point (occupant packaging standards).

To fill this gap, an alternative approach, Body Shape Alignment, is presented to reduce the subjectivity involved while considering the standards for occupant packaging. Figure 6 summarises the main steps of the proposed approach.

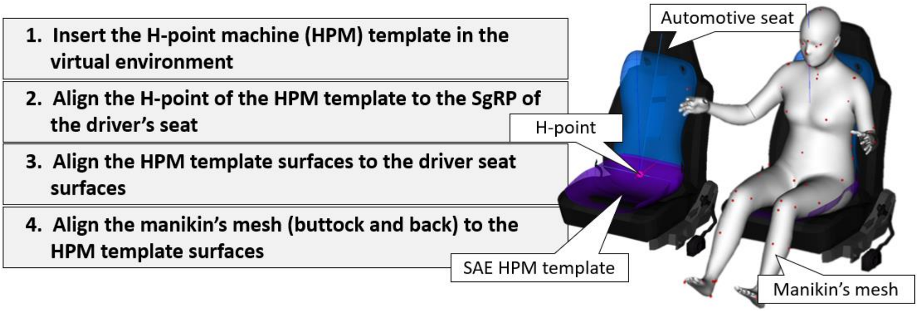

Figure 6. Body Shape Alignment approach.

The Statistical Prediction and the Body Shape Alignment approaches were compared to sit manikins in virtual driving environments considering a wide range of body mass index (BMI) on human body meshes. Fourteen human body meshes (seven females and seven males) were obtained from the BioHuman website (UMTRI BioHuman, 2022). The anthropometric measurements of each manikin mesh were generated from two three-dimensional boundary ellipsoids with a confidence level of 90% (Brolin et al., 2012). One ellipsoid for each sex, based on stature, body weight, and sitting height. The anthropometric data was taken from the CAESAR data set (Robinette et al., 2002). An average and six manikins defined at the ends of the three axes of each ellipsoid were selected. Results showed that manikins with higher BMI move forward in the x-axis using the Statistical Prediction approach. This might not be seen as a problem, however, these differences could result in notable gaps between the manikin mesh and the seat geometry. Visually, the manikin mesh was visualized as floating over the seat geometry, not in contact with it. This potential gap means that the Statistical Prediction method may require manual adjustments to fix the manikin-mesh and seat-geometry mismatch. On the other hand, the spread in the x and z axis is not as wide using the Body Shape Alignment approach.

Although the presented Body Shape Alignment predicts the mid-hip to H-point location of the automotive seat in a standardized way considering standards and human body shape variability it still needs further development, such as the definition of appropriate constraints between the vehicle geometries and the manikin mesh. Going further, the use of this approach for obtaining a proper initial driving posture relies on, and therefore requires, accurate human body meshes within DHM software, which in the current state still have limitations. In addition, the accuracy of the Body Shape Alignment approach could be further advanced by implementing models regarding seat foam and human buttock deformation (Wang et al., 2021). Lastly, Paper II also reflects on the difference between mid-hip to H-point locations using different approaches and the diversity in human anthropometrics and behaviour. Future research should focus on identifying the criteria for postural variety and determining what constitutes an accurate initial driving posture. One potential approach to address these questions is by incorporating standard error measurements of specific models derived from statistical studies. However, further research is still needed to predict and understand potential vehicle interactions accurately.

4.3 PAPER III (WORK IN PROGRESS)

Simulation-based multi-objective optimization for occupant packaging design (Journal paper in progress)

Paper III investigates simulation-based multi-objective optimization as a method for automotive ergonomics or occupant packaging design. This approach is used to address subjectivity and usability issues observed in Papers I and II while considering body dimensions and behavioural variability. Simulations of driving posture in the virtual environment are typically done following the DHM standard procedure. The DHM standard procedure involves several issues, as described in Paper II.

On the one hand, one of the major problems with the DHM standard procedure is its manual nature which leads to several usability issues. Because it consists of a manual procedure, typically time-consuming processes are necessary for doing simulations, while at the same time, there is an unspecified subjectivity involved in the simulations by DHM users causing non-repeatable results. These aspects affect usability in a negative way since such subjectivity introduces inconsistencies and inaccuracies that may lead to incorrect decision-making in the automotive ergonomics design. The lack of relationship between the mid-hip and the H-point is another aspect affecting the usability issues of the DHM standard procedure.

In addition, another issue of the DHM standard procedure is the lack of human behavioural variability consideration. As it currently works, described in Paper II, DHM users make the manikin or manikin family assume the driving posture, which is generally defined by the DHM software following specific body joint angles values regardless of the manikin's body dimensions or vehicle model. Such body joint angle sets of values are based on previous studies about driving posture (Schmidt et al., 2014; Gkikas, 2016), which are generally deterministic, giving a single set of values for driving, typically the average. Although the initial driving postures of a manikin family with different body dimension measurements is modified by the definition of various constraints between the manikin's mesh and the automotive geometries of the vehicle, the DHM tool optimizes the manikin's posture following such a deterministic set of values for body joint angles along all manikins regardless their body dimensions. This is something to consider since human variability has been observed for different human body dimensions in previous studies (Kyung and Nussbaum, 2009; Park et al., 2016b; Bubb et al., 2021). For example, shorter people typically sit forward and higher within the seat adjustment range, whereas taller people typically prefer backward and lower positions within the seat adjustment range, changing in this way the body joint angles for different body dimension measurements. Going further, there may be the case that people with similar body dimensions also behave differently and adopt driving postures substantially differently. That means human variability depends on differences in body dimensions (anthropometric variability) and behaviour (e.g., postural). None of the aforementioned sources of human variability, body dimensions and behavioural variability, are nowadays considered in DHM tools' posture prediction.

Simulation-based multi-objective optimization (SBMOO) is presented in this paper as a method to improve simulation usability issues for automotive ergonomics design while considering human body dimension and behavioural variability. SBMOO is a process that uses computer simulations to find the best possible solution to a design problem involving multiple conflicting objectives. In this process, the objective functions are evaluated by running simulations on a model or a set of models that represent the real-world system being analysed. Several SBMOO characteristics make the consideration of using this approach in automotive ergonomics design evident. Firstly, the SBMMO's definition closely aligns with the ergonomics designers' work objective identified in Paper I, i.e. balancing multiple conflicting aspects. This means that using the SBMOO approach aims to identify an optimized solution(s) that balances the optimization objectives or considered aspects simultaneously rather than just optimizing for a single objective. Secondly, this approach can reduce the usability issues involved with the DHM standard procedure. The subjectivity involved by DHM users, non-repeatable results, and time-consuming manual procedures could be improved since simulations would operate automatically. And thirdly, human anthropometric and behavioural diversity can be included in the SBMOO process by considering each manikin as one and different objective. While the term usability relates to efficiency, effectiveness and satisfaction, SBMOO mainly refers to and contributes to the enhancement of efficiency. However, SBMOO may also contribute to enhancing effectiveness. By leveraging the SBMOO approach, generating and evaluating a significantly larger number of design alternatives is possible compared to manual methods. This extensive exploration of the solution space increases the likeliness of finding a better design solution, positively impacting effectiveness.

In this paper, SBMOO is applied to solve a made up, but possible, design task in which ergonomics designers are to find a design solution considering both ergonomic and non-ergonomic aspects. Large ranges of adjustments for all components (e.g. seat and steering wheel) would accommodate almost all drivers. However, components' adjustability ranges are restricted by safety, costs, design dimensions, or other constraints. The example scenario represents a situation in which ergonomics designers are to find an optimized design solution by considering ergonomics aspects of an existing product (optimization objectives) having restrictions from other automotive development departments such as design or safety (optimization constraints). In more detail, the goal of the SBMOO in this paper is to find an occupant packaging design that is shaped by the location(s) of seat and steering wheel adjustment ranges, fixed in size, so that the maximum number of manikins in a family is within an acceptable posture (optimization objectives). A method to define what is regarded as an acceptable posture is established using the preferred angles and the root mean square error (RMSE), given in Park et al. (2016b). This data is used to establish angle ranges, that in turn define whether a specific posture is classified as "OK" or "NOT OK". Using this method, the preferred angles vary depending on the anthropometric measures of the manikins. Fourteen manikins with different body dimensions have been defined to consider human variability. Other factors that affect the preferred joint angles are age, gender, and vehicle layout measurements, which have also been considered in the study.

Further, by including the RMSE data from Park et al. (2016b), human postural variability is considered. This serves to define an acceptable range for each manikin rather than a unique optimal value, which is believed to be a more realistic approach considering that there exists a postural variability. In this way, each manikin's body joint angle calculated based on their body dimension has a range of postural variability instead of a deterministic solution. In short, the statistical prediction methods for calculating the driving posture of each manikin with different body dimensions and the RMSE of each of the body joint angles constitute the ergonomic evaluation method, which in turn are the multiple optimization objectives of the study. Since fourteen manikins are considered, the SBMOO example will have fourteen objectives, one per manikin. However, while the statistical prediction models from Park et al. (2016b) are used in this paper, as an example, other research studies or results from companies' own studies could be defined as ergonomic evaluation methods when using the SBMOO approach.

The model used for the SBMOO of this study consists of a 3D digital model of the driver, the seat (H-point machine template), the steering wheel, the foot pedals, and the windscreen. The manikin (driver) has been seated following the Body Shape Alignment approach (introduced in Paper II). Different constraints have been defined in the virtual environment to align the manikin's mesh to the H-point machine template (Body Shape Alignment) and get an accurate and automatic driving posture: driving feet in the pedals, buttock and lower back points of the manikin to the H-point machine template, hands on the steering wheel. Figure 7 shows the driving scenario in the IPS IMMA DHM tool with the defined constraints and one manikin of the manikin family.

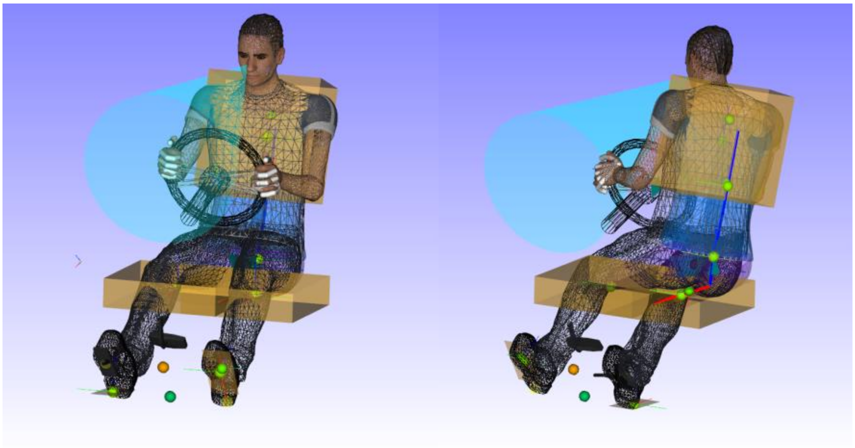

Figure 7. SBMOO scene: manikin seated following the Body Shape Alignment approach and defined constraints.

Paper III is a current work in process and with results still pending.

4.4 PAPER IV (WORK IN PROGRESS)

Steering Dynamics model: a validation study for reachability tasks in occupant packaging (Journal/Conference paper in progress)

In cognitive science, human motions have also been defined using dynamical system methods, apart from data and optimisation-based methods (Fajen and Warren, 2003, 2007). That means considering specific patterns or regularities observed and describing people's movement data. One example is the Steering Dynamics Model (SDM), which demonstrates how one can steer towards desired locations avoiding obstacles (Fajen and Warren, 2003). The authors of SDM believe there is a need to integrate dynamical and information-based approaches for more complex, adaptive behaviour depending on interactions with the environment.

The SDM consists of a system of differential equations, with attractors and repellers corresponding to goals and obstacles. It generates a trajectory through the task space, a sequence of headings and turning rates for a given travel speed. The SDM has two different components. One component accurately simulates people's paths when walking to a stationary goal, while the second component reproduces and predicts routes detouring obstacles. The present study focuses on the first component, paths to stationary goals in 2D (Equation 1), and expands it to the three-dimensional (3D) space.

$$\ddot{\phi} = -b\dot{\phi} - k_g\left(\phi - \psi_g\right)(e^{-c_1 d_g} + c_2) \qquad (1)$$

The parameters of Equation 1 are: b, k_g, c_1, and c_2. The authors define heading (ϕ) as the direction of locomotion concerning an allocentric reference axis, and bearing (ψ_g) as the direction of a target concerning the same axis at a distance d_g. Parameter b expresses the ratio of damping to the body's moment of inertia in units of s^{-1}; k_g expresses the ratio of stiffness to a moment of inertia in units of s^{-1}; the constant c_1 determines the decay rate with distance in units of m^{-1}; and c_2 determines a minimum value so acceleration does not go to zero at large distances and is dimensionless. For a detailed description and complete understanding of SDM, see Fajen and Warren (2003).

Different values of its parameters strongly affect and change the steering and route model performance. This means that working with the correct parameter values is crucial for obtaining reliable results. Fajen and Warren (2003) provided a set of values from their experimental results, which was defined as default for the continuous steps in this study. Default parameter values are b = 3.25, kg = 7.50, c1 = 0.40, and c2 = 0.40.

So far, the SDM or human path model has been implemented and validated in 2D space applications. Paper IV expands the SDM to the 3D space, considering the orientation of the agent in the space, and validates it with reachability tasks in occupant packaging contexts. In this context, an agent refers to a mobile organism that interacts with its environment and regulates its behaviour based on information from the environment. This extension to the 3D space may have great potential in different research fields and applications in the industry, not only for DHM in occupant packaging but also in other areas such as robotics and human-robot collaboration.

Transformation matrices and/or quaternions are ways to solve the path planning in the 3D space with 6 degrees of freedom, i.e. translation and rotation along the three axes. The SDM 3D approach will be validated with motion capture data from 10 subjects performing four reachability tasks in occupant packaging contexts. Dynamic time-warping series will be used to compare similarities between the SDM trajectories and real data recordings to validate the expansion of the model.

Paper IV is currently work in process and with results still pending.

The successful development of this study could constitute initial proof of how considering human motion research from other fields could potentially benefit design engineering and the development of DHM tools. Going further, SDM could be combined or refined in different ways. Firstly, it could be combined with IK solvers currently used in DHM tools, or with other solvers, such as FABRIK (Aristidou and Lasenby, 2011). Secondly, the default parameter values and the velocity function provided by (Fajen and Warren, 2003) may not be optimal for the reachability tasks in a driving situation. Therefore, further studies could be done to accurately define the model's parameter values for different tasks. And third, this paper is limited to the first part of the equation model of steering at goals, which corresponds to the first experiment out of three in the study by Fajen and Warren (2003). Future research may address the implementation of obstacle avoidance and interception of moving objects in the 3D space (Fajen and Warren, 2007).

CHAPTER 5
DISCUSSION

This chapter discusses the current state and future directions of this thesis proposal. Research results from each paper and its contributions in light of the research questions and objectives are covered. Finally, this chapter presents a plan for the upcoming research activities in the remaining time of this thesis.

5.1 ANSWER TO RESEARCH QUESTIONS

The following section discusses how the summarised papers' results relate to the research questions and to what extent these questions are answered so far. Two papers have been published, and two other studies are in current development in this thesis. How these relate to the research questions and objectives stated in Chapter 1 is shown in Table 1.

Table 1. Papers contribution to research questions and objectives.

	RQ1	RQ2		RQ3
	O1	O2	O3	O4
Paper I	x			
Paper II	x	x		
Paper III		x		
Paper IV				x

RQ1: How are DHM tools used for addressing ergonomics in automotive development processes?

O1: Characterize the use of DHM tools for addressing ergonomics during the product development process in the automotive industry.

Chapter 2, "Frame of reference", and results from Paper I show that ergonomics designers across automotive companies employ DHM tools in PD. Paper I reports that DHM tools are used for making predictions, analyses, and validations during internal and external balancing. These are the most relevant steps for ergonomics designers through the different product design phases. Internal balancing refers to achieving a balance between various ergonomic factors that impact the end user's experience, whereas external balancing involves achieving a balance between ergonomic and non-ergonomic considerations during the PD process. Although DHM tools are mainly beneficial for aiding a proactive design process and its possibility of human anthropometry diversity representations, among others, they also have some key limitations affecting the workflow of PD. Literature reports a lack of usability, cognitive aspects and inaccurate postures and motions as some of the main limitations within DHM tools. Paper I validates these limitations and identifies four state of the art gaps or future research directions in the field and within the Swedish automotive industry concerning DHM tools: human behaviour predictions, simulation tool's usability, ergonomic evaluation methods, and integration between systems. The human behaviour predictions and simulation tool's usability gaps motivated the development and focus of RQ2 and RQ3 of this thesis proposal.

Further, Paper II focuses on these challenges: human posture and motion predictions and the usability of DHM tools. It provides a deeper understanding of the main limitation DHM users face when it comes to simulations of initial seated driving posture. The core problem is the lack of a relationship between the seated reference points used by vehicle designers and the human kinematic models used in DHM tools. In addition, the mesh appearance of manikins in DHM tools can complicate it even more. That may lead to different and inaccurate predictions related to collision volumes that determine the manikin's boundaries relative to seat geometry. This means that even in possibly accurate predictions between human body models and standards guidelines, ergonomics designers rely on their perception to modify and quantify the driver's seat position until manikin body shape and automotive geometries would look appropriately aligned. Results from the literature, Paper I, and Paper II motivate the need for developing methods and models enabling usable and accurate results supporting the decision-making in occupant packaging design.

While Paper I only considers automotive companies in the Swedish industry, results are deemed generalizable since they were corroborated in the literature.

RQ2: How can the usability of human-product interaction simulations be improved for providing decision support in the automotive development process?

O2: Refinement and/or development of methods improving the usability of DHM simulations for analyzing human-product interaction in automotive ergonomics contexts.

Quantifying the initial seated posture is crucial for ergonomic and safety evaluations because the design and development of other ergonomic requirements, such as seated posture comfort, operating controls, and interior and exterior visibility, depend on it. New and refined methods are presented in papers II and III for quantifying initial seated driving postures while improving usability and facilitating decision support in the automotive ergonomics development process. Paper II discusses different approaches for achieving an initial seated driving posture and its benefits and constraints. It further introduces the Body Shape Alignment approach, which is a method used to standardize the points in human models for seated driving postures in DHM tools. The Body Shape Alignment has been further expanded after its publication, including different constraints for a consistent alignment (Figure 8).

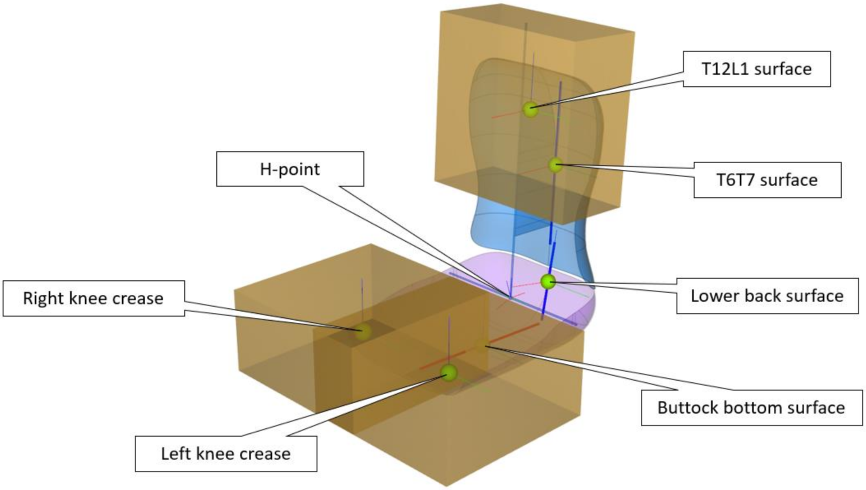

Figure 8. Constraints for Body Shape Alignment approach.

In addition, Paper III suggests using a simulation-based multi-objective optimisation approach to improve DHM decision-support and usability in occupant packaging or automotive ergonomics design during internal and external balancing tasks while considering human diversity. While Paper III exemplifies a scenario in which ergonomics aspects are to be balanced with non-ergonomic aspects (engineering design and safety), such example could be further developed and benefit different phases of the PD process. For example, achieving a balance between various ergonomics aspects in a predevelopment stage. The undefined subjectivity involved by DHM users in driving simulations and non-repeatable results are addressed with the proposed methods in Paper II and Paper III. Further, the PD process can be quicker and more proactive since time-consuming simulations and validation processes can be accelerated using more consistent and reliable methods.

O3: Evaluation of developed methods for improving the usability of DHM simulations with automotive ergonomics designers in the industry.

There are no papers addressing O3 so far in this thesis proposal. It will be one of the focuses in the remaining time.

RQ3: HOW CAN HUMAN MOTION PREDICTIONS IMPLEMENTED IN DHM TOOLS BE IMPROVED FOR AUTOMOTIVE DEVELOPMENT PROCESSES?

O4: Consideration of human motion models in different research fields for improving the understanding and developing models that increase human motion simulations' accuracy in automotive ergonomics contexts.

Paper IV, which is currently an ongoing work, investigates if there is potential to consider human motion research results from other research fields in automotive ergonomics contexts within DHM tools. Paper IV expands to the 3D space and tests the validity of a human path planning model developed in the cognitive science field, here applied for reachability tasks in driving scenarios. The remaining results from such validation can help guide the refinement of the path planning model for automotive contexts following different approaches, such as obtaining the correct set of parameter values of the model for the reachability tasks, the development of a velocity function, or combining the model with an IK solver like FABRIK (Aristidou and Lasenby, 2011).

5.2 RESEARCH PLAN

This section offers a research and publication plan to continue developing this thesis in the remaining time (Figure 9). To complete this thesis, the research questions must be answered to a greater extent. So far, most of this thesis work has focused on RQ1 and RQ2. RQ1 is considered to be answered, and RQ2 is partially answered. Future research will therefore focus on RQ2 and especially on RQ3, developing and/or refining current human motion methods and models for improving usability and accuracy of human-product interaction simulations. The main focus during the remainder of 2023 is finishing Paper III and Paper IV, contributing to RQ2 and RQ3, respectively. During that time, two other studies (Paper VI and Paper VII) will focus on RQ3. Paper VII will focus on refining the path planning model. Refining the path planning model for automotive contexts may follow different approaches such as obtaining the correct set of model parameter values for the reachability tasks, developing a velocity function, or combining the model with an IK solver like FABRIK. The approach to continue with the path planning refinement will be based on results from Paper IV and further discussions within the research group.

On the other hand, Paper VI aims to compare predicted seated driving postures using both, statistical predictions and DHM simulations of H-point, steering wheel position and eyepoint, with results measured in real vehicles. Inaccurate results obtained in Paper VI will lead to an in-depth study and understanding of human-vehicle interactions considering research from other research fields and suggesting possible changes for improving DHM simulation predictions. To continue answering and completing the objectives from RQ2, Paper V aims to evaluate the developed methods in the last period of this research with industrial partners. This evaluation study will include simulations of driving postures and motions in DHM tools to measure the potential usability improvement using the developed methods. Literature review and thesis writing are activities that will be addressed during the entire duration of the research to keep a well-documented and updated report of activities and results.

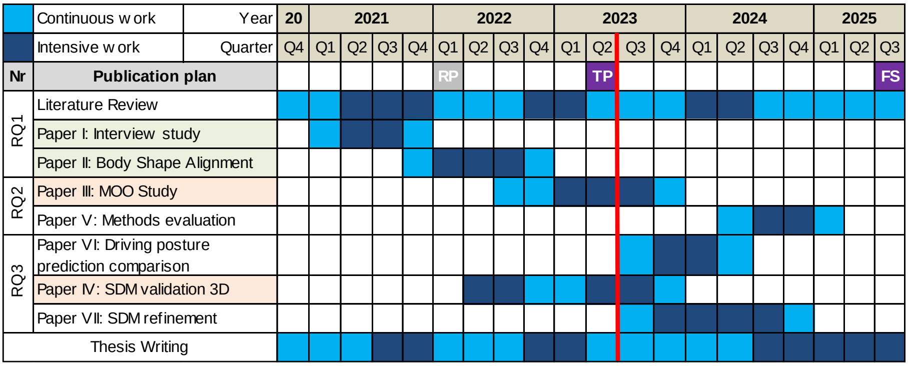

Figure 9. Publication plan for the remaining time.

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