

# Synergistic Integration of Physical and Digital Simulation of a Shoulder Exoskeleton

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**Abstract** – Support systems for humans are becoming an important aspect in today's workplace due to the increasing workload and need for productive tasks. For this purpose, industrial exoskeletons are a promising approach, especially for physically demanding tasks. To develop, evaluate, and optimize assistive systems, it is necessary to build a comprehensive understanding of these systems by investigating their dynamics and kinematics. This can be achieved by simulating all interacting components, including the task, the human, and the robotic system. This paper describes a synergy of various elements to overcome the challenges while researching and developing exoskeletons.

**Keywords** – Exoskeleton, motion capture system, robot control, virtual reality

## I. INTRODUCTION

Exoskeletons, also known as wearable robots, represent a cutting-edge advancement in the field of assistive technology and robotics [1]. These devices are designed to augment, reinforce, or restore human performance by providing external mechanical support. Initially conceptualized for military applications, exoskeletons have since found significant applications in medical rehabilitation, industrial ergonomics, and personal mobility enhancement. [1]

The use of simulation techniques is crucial in the development and implementation of exoskeletons. Without the requirement for large physical prototypes, simulation offers a virtual environment for designing, evaluating, testing, and refining exoskeleton ideas under considered settings. This method finds possible challenges early in the design phase of such systems, which speeds up development, lowers costs, and improves safety. Additionally, a variety of real-world conditions can be replicated using simulations, which enables researchers to maximize exoskeleton performance and ergonomics. Exoskeleton development is dependent on the identification and study of particular use cases. Use cases offer realistic circumstances that direct exoskeleton technology development, testing, and improvement.

However, available data indicates that a variety of industrial tasks and user attributes have a major impact on how effective exoskeletons are [2]. A training framework that can allow employees to experience various exoskeletons in their workplace while gaining the motor skills required to operate an exoskeleton safely and effectively is needed, as exoskeleton operation needs to be meaningfully and effectively integrated

into the job or work context and there is a great deal of diversity in user, work, and exoskeleton characteristics. Virtual reality, another Industry 4.0 technology, has demonstrated an excessive amount of interest in taking human factors into account throughout the lifetime of various industrial operations and products [3], [4], particularly when conventional technologies and decision support tools are insufficient to address novel difficulties [5]. These days, a broad spectrum of enterprises employ virtual reality for a variety of purposes, including education, decision support, product review, maintenance assistance, reproducing industrial activities, enhancing resource planning, and more. Virtual reality has demonstrated its usefulness in practical production. Lastly, evaluation techniques are crucial for producing insightful data and carrying out an unbiased investigation of the impacts of exoskeletons in a real-world workplace [6], [7]. The majority of recent research lacks standardized parameters or higher sample sizes [8], [9].

In order to benchmark exoskeletons uniformly, the EVO-MTI project has taken the lead in this regard and created a framework and methodology for harmonizing the testing of assistive robotic systems performance. Improving robotic systems' comparability and reproducibility as well as developing a new system is the aim. This paper aims to create various physical and digital simulations, integrate the resulting data into a comprehensive database, and introduce a methodology for using this data in exoskeleton development.

## II. METHODOLOGY

Relevant hardware-level infrastructure components are further introduced in the sections that follow. Additionally, relevant analytical techniques that can offer valuable data for simulation models are described. A variety of physical prototypes that can reproduce different scenarios are used, as seen in Figure 1. These prototypes simulate scenarios with and without (S1) assistance. Then, a simulation of the exoskeleton (S2A) is performed, and then a simulation of the human model (S2B). Ultimately, these prototypes are combined into a single, comprehensive simulation (S3) [10]. These parts are implemented individually or together depending on the iterative stage of the transdisciplinary development process.

### A. Simulated Use Case

In this scenario, different tasks are replicated and can be performed without or with exoskeletons in a standardized laboratory environment. A test parkour is used to summarize different physically demanding tasks like baggage lifting, nursing, construction or assembly line. Users can use different exoskeletons while performing the same task.

For this, use cases play a vital role in the development and evaluation of exoskeletons, providing real-world scenarios that guide the design and evaluation of these devices. By analysing specific use cases, developers can identify common repetitive motions, errors associated with it and stress induced in muscles during the task allowing for targeted improvements in exoskeleton design. The importance of simulating use cases is listed below:

- Design Optimization: Use cases help in understanding the specific demands of different tasks, allowing engi-

neers to design exoskeletons that can support and enhance repetitive motions effectively. This includes optimizing the range of motion, joint alignment, and load distribution to minimize stress and strain.

- Performance Evaluation: Evaluating exoskeleton performance in real-world use cases is essential for identifying potential errors and inefficiencies. This involves assessing the device’s ability to reduce fatigue, enhance performance, and maintain consistency in repetitive tasks.
- User-Centred Design: Engaging users in specific use cases provides valuable feedback on the usability and comfort of exoskeletons. This feedback is critical for making iterative improvements that ensure the device meets the needs and expectations of users in performing repetitive motions.

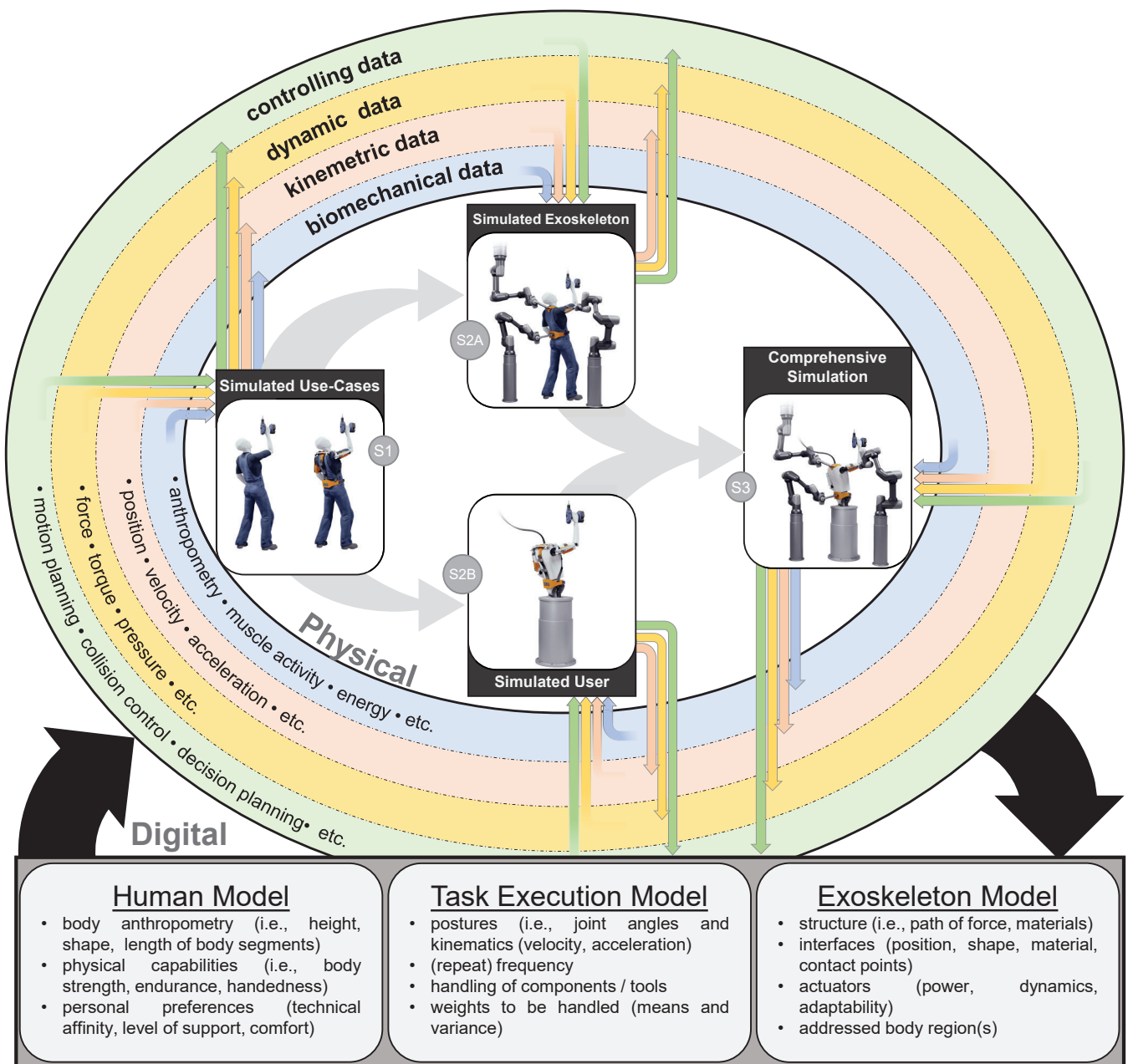


FIGURE 1: DATASTREAM AND ELEMENT CONNECTION WITHIN THE DEVELOPMENT ENVIRONMENT

## B. Simulated Exoskeleton

Besides using real exoskeletons, the simulation of exoskeletal characteristics in a robot-based environment by using cobots is implemented in this scenario. Relevant exoskeletal properties are modelled and simulated by multiple cobots where interaction occurs at the coupled elements that is the exoskeletal interfaces. Parameterizable properties of the exoskeleton such as joint states, and control parameters acting at the same physical interfaces are needed to simulate the exoskeleton and it is carried out in an environment that tracks motion trajectories and provides defined forces and torque.

## C. Simulated User

Repetitive human motion is integral to many use cases but is often accompanied by challenges such as stress, strain, and errors. The development of exoskeletons that can effectively support these motions requires a deep understanding of biomechanics and the specific demands of various use cases. By leveraging detailed use case analysis, developers can design exoskeletons that enhance performance, reduce physical strain, and minimize errors in repetitive tasks. This approach not only improves the functionality and safety of exoskeletons but also ensures they are tailored to meet the real-world needs of the users. Challenges in repetitive motion are as follows:

- **Stress and Strain:** Continuous repetition of the same motions can lead to muscle stress and strain, increasing the risk of injuries. This is particularly problematic in industrial settings where workers are required to perform repetitive tasks for long hours.
- **Biomechanical Variability:** Individual differences in anatomy and biomechanics mean that the same task can be performed differently by different people. This variability can lead to inconsistent performance and potential inaccuracies.
- **Motor Learning and Control:** Learning and controlling repetitive motions involve complex motor processes that can be prone to errors. These errors can result from incorrect movement patterns, lack of coordination, or inadequate feedback mechanisms.

In order to reduce the tiredness of the user while performing a repetitive task, achieving standardized movements to improve the possibilities of comparing different systems as well as to measure the additional aspects like joint torque, humanoid-like robot simulate human movements.

## D. Comprehensive Simulation

Humans, tasks and exoskeletons are physically simulated simultaneously in this scenario. Simulation is done using cobot coupling and testing platforms. This stage highly depends on the S2A and S2B's technical realization.

## III. IMPLEMENTATION

### A. Simulation of exoskeleton properties

In order to simulate the exoskeleton properties, a Robot Operating System (ROS) based platform as shown in Figure 2 is developed for simulating the exoskeleton properties and controlling the cobot accordingly. The Vicon node streams the real-time data of the markers detected in the motion capture environment and calculates the shoulder arm angle accordingly. This data is then used to calculate the simulated support torque in the Exo Node. The necessary support characteristics in the form of different support curves can be imported in this

node. The human pose and support torque are used as an input for generating the trajectory and torque of the cobot. A force torque sensor attached between the end effector of the cobot and the interface helps formulate a feedback loop for the control of the cobot.

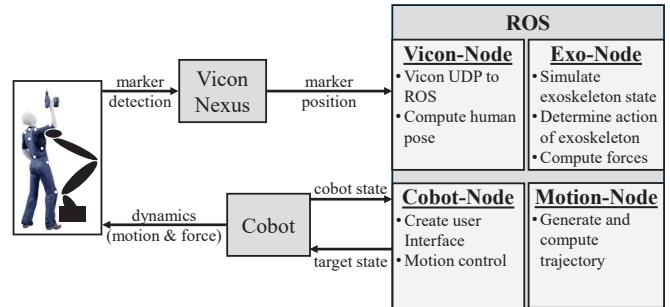


FIGURE 2: ROS ARCHITECTURE FOR SIMULATING EXOSKELETAL PROPERTIES

The Exo node can simulate multiple exoskeletons that provide different support characteristics at different interfaces. In the implementation below, the shoulder exoskeleton Lucy [11] is used for the simulating support torque based on the angle of the arm. The use case used here is the above-head drilling motion. The user is attached with markers at the arm, shoulder and hip as shown in Figure 3 in the form of red spheres. This is done in order to gain the shoulder angle of the user while the user is performing the task in the Vicon motion capture environment.

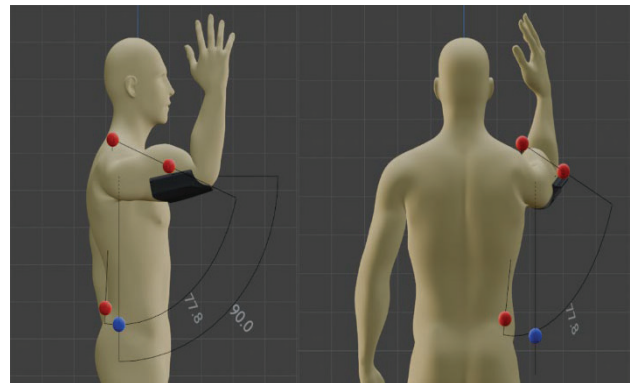


FIGURE 3: SIMULATION OF ARM ANGLE

In Figure 3, a visualization of the human model in Blender is shown. The shoulder arm angle calculated in the Vicon node in ROS is realized with respect to the actual arm angle. Here, the actual shoulder angle (90°) and calculated shoulder angle (77.8°) are illustrated. This error occurs since the shoulder joint of a human being, having seven Degrees of freedom (DOF), is a complex joint to simulate, the human error caused during the placing of markers that are not aligned as per the actual joints and the inaccuracy caused by motion capture due to blind spots.

Figure 4 illustrates the graph between the actual arm angle vs. the arm angle calculated by the Vicon node in ROS based on the three-marker set. The red and blue plots are data acquired by two test persons. In order to fit the curve, a regression is performed which is then exhibited by the grey line.

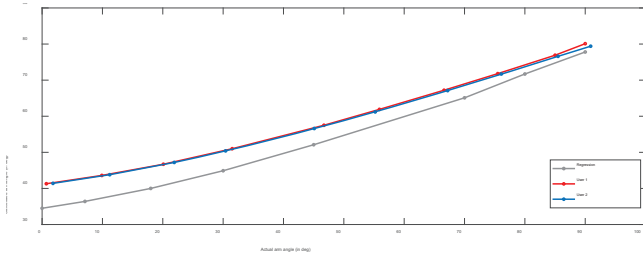


FIGURE 4: REGRESSION FOR COMPENSATION OF ANGLE DIFFERENCE

In order to calibrate this error in the tracking arm angle, a localization algorithm in addition to a regression model is implemented. For this, every test person has to initially hold the arm position at standard angles ( $0^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ ,  $90^\circ$ ). The standard angles can then be manually entered in respect to the tracked arm angle. The calibration algorithm is then implemented on this data to give a localization output to correct the error of the tracking system.

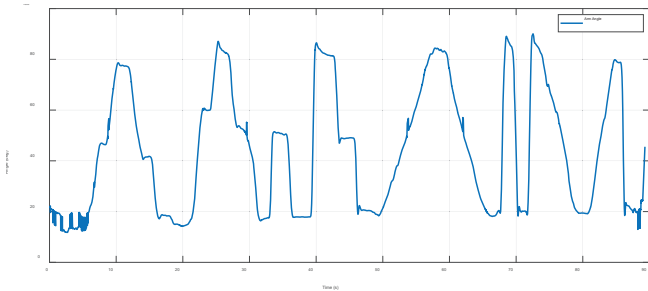


FIGURE 5: CALCULATED ARM ANGLE IN A CYCLIC MOTION

Since the use cases have to be realized by a repetitive motion, it is then observed in Figure 5 that while the test person performs a cyclic drilling motion eight times, the reach of the shoulder arm angle as well as the acceleration of the arm keeps differing. The test person may not be familiarized with the task and is in a new environment, which may cause this human error.

For the purpose of reducing the error in angle calculation and obtaining a standardized use case data for simulating and realizing different scenarios, an approach to simulate a human motion, is discussed.

### B. Humanoid

The implementation of robotic-based systems can facilitate the achievement of high reproducibility of human movements. Collaborative robots (cobots) are utilized to model human-like movement. In addition to their compact dimensions, cobots are distinguished by their versatile parameterization, mobility, and integrability for this purpose. In a methodology outlined in [12] a physical arm, constructed as a 3D-printed part, is attached to the end effector of a seven-axis Franka Panda cobot. As shown in Figure 6, the exoskeleton is positioned on a stand, and the 3D-printed arm is coupled to the arm shells of the exoskeleton. Previously recorded motion data from the motion lab were utilized and implemented to the cobot allowing for the execution of the movement by the 3D printed arm and the collection of data for further investigation.

### C. Virtual Reality

In this section, we shall discuss the implementation of virtual reality (VR) in the development and evaluation process of this project. The virtual reality approach can help reduce

human error. Data analysis to control parameterizable properties, realization of the influence of various sensors that are integrated will get easier. It will also play a crucial role in getting the test person familiarised with the task and guiding them to perform the task and not get distracted due to a wearable robot attached to the body of the test person. Evaluation of exoskeletons requires testing different exoskeletons in different use cases. Building a test station to realize multiple use cases can be difficult due to lack of space. The integration of VR will also benefit with respect to building multiple test stations to realize different use cases. A VR environment will give the option to customize use cases and tools as needed. The position of the controller in the VR environment will also aid as an efficient feedback loop for the arm angle calibration. A safety approach can also be induced in this environment where the user can communicate via a controller when some technical issues are occurring. An alert when a malfunction occurs in the robotic system can be visualized in the VR environment.

The future work in this project is to use the Quest 3 VR headset in combination with a Unity 3D software platform. In Figure 7, a flowchart of the workflow of the VR environment is presented. The idea is to take in user inputs via the VR controller as well as use the motion capture for calibration of the position of the test person in the VR environment. In the next step, the test person will be given the choice to choose which exoskeleton they are currently wearing in the VR environment. All data such as the accuracy of the task performed, acceleration, and position of the controller will be logged.

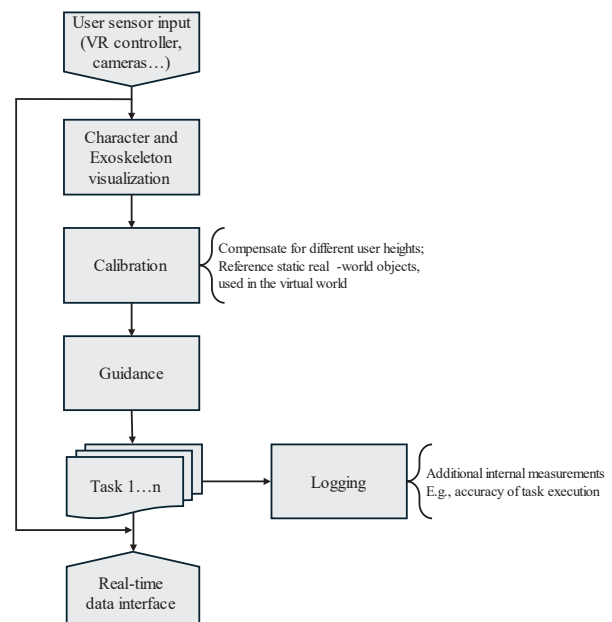


FIGURE 7: VIRTUAL REALITY FLOWCHART

## IV. CONCLUSION

Despite the number of studies carried out to date, there are still a number of issues with research methodology and exoskeleton evaluation. An assessment of the systems in actual working environments is required to comprehend their consequences. Standardized test protocols are also necessary to obtain a sizable and comparable data set.

Towards this goal, this paper presented a plan to collaboratively progress the emerging development and evaluation of

exoskeletons by strengthening the exchange between developers, researchers, and end users and collecting data in the future. In a continuous, multicentric prospective study strategy, this should be helpful to add more data sets.

It will be possible to test and assess exoskeletons in specially designed Parkours, where working conditions are as close to the real-world as possible. This allows research data to be generated specific to an exoskeleton and allows for intraindividual comparisons of exoskeleton users.

The synergy of various core elements provides a foundation for standardizing use cases, which enables a systematic investigation of exoskeletons. This standardization then allows for the variation of parameters, which in turn facilitates the optimization of support systems at both the hardware and software levels. Furthermore, the integration of these core elements into a virtual reality environment allows for the investigation of human perception and the acceptance of support systems through immersion.

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