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PARTICIPATORY ERGONOMICS USING VR INTEGRATED WITH ANALYSIS TOOLS

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ABSTRACT

This paper presents our work on the integrated use of simulation tools in *real time* for participatory occupational ergonomic studies. The focus of this paper is a synergistic system that consists of an interactive immersive simulation tool that has been developed in-house and integrated with a commercial human modeling simulation system, Jack™. The impetus of the real-time integration is to allow the complementary use of two powerful simulation tools by allowing the user to perform the task naturally in an immersive environment, while the body posture information is *continuously* and automatically passed to the human modeling system for a *continuous (and not discrete) analysis* of the participatory ergonomic issues under consideration. This facilitates integration of ergonomic issues early in the design and planning phases of workplace layouts, even where the physical facility does not exist. The proposed integration is demonstrated using a manufacturing example.

1 INTRODUCTION AND MOTIVATION

Workplace ergonomic considerations have traditionally been reactive, time-consuming, incomplete, sporadic, and difficult. Experience of an expert in ergonomic studies or data from injuries that have been observed and reported previously have always been necessary for these studies and analyses after problems are noticed in the workplace. There are now emerging technologies supporting simulation based engineering and several operational simulation based engineering systems to address this in a proactive manner. At present various commercial systems are available for ergonomic analysis of human posture and workplace design. However, these methods provide primarily *static analysis* of the task at hand i.e. one can model a static "snap shot" of the posture or situation to be evaluated and then perform an analysis using the tool.

In recent times, virtual reality technology is another technology attaining maturity and gaining acceptance in industry (Nomura and Sawada 2001). Application of this technology spans health-care, national security, design and manufacturing (Wang et al. 2001), education, and training (Li et al. 2003). The interactive nature of VR systems lends itself particularly well to participatory ergonomics studies. Hence, one natural application domain of these immersive technologies is in ergonomic studies such as reach, visibility, and visual inspection through the use of CAD models in immersive environments. However, most of the environments only allow for subjective and qualitative evaluations based on verbal/written participant and observer feedback of comfort and effectiveness.

In the work presented, we synergize the ergonomic modeling and setup capability of an immersive visualization/simulation system with a commercially available ergonomic tool to perform a rigorous analysis of the underlying ergonomic aspects during the simulation in the immersive environment (Figure 1). This presents a very effective approach to take the evaluation capabilities to the next level by providing a monitoring system that analyzes the entire process continuously, in real-time, and flags areas that are not ergonomically recommendable as the task is being performed in the simulated environment. The focus of the study is on "Industrial Ergonomics" or "Occupational Biomechanics," a branch of ergonomics that concentrates on the physical aspects of work and human capabilities such as force, posture, and repetition.

Thus, the approach was to develop a dynamic analysis tool for ergonomics studies by expanding on the use of an immersive system through the addition of rigorous ergonomic analysis functionality. The use of available dedicated software for analysis eliminates the need to rebuild the algorithms and does not induce a performance overhead in the simulation system. It assists in "participatory ergonomics", which means that the worker can perform the re-

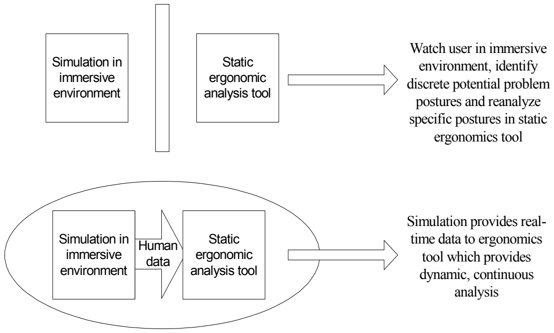

Figure 1: Comparison of Existing Methods vs. Method Presented in this Paper

quired tasks in the immersive environment before the actual tasks are performed in the workplace. Such integration will help in proactive ergonomics by allowing the designer to consider more workplace configurations and design changes while the workplace is still in the design stage, thus reducing the risk of ergonomic problems occurring later on.

2 RELATED WORK

The importance of applying ergonomics to workplace design is illustrated by the Injuries, Illnesses, and Fatalities (IIF) program of the U.S. Department of Labor, Bureau of Labor Statistics (2001). According to the report there were 5.2 million occupational injuries and illnesses among U.S. workers and approximately 5.7 of every 100 workers experienced a job-related injury or illness. Workplace related injuries and illnesses increase workers' compensation and retraining costs, absenteeism, and faulty products. Many research studies have shown the positive effects of applying ergonomics principles in workplace design (Das and Shikdar, 1999). Riley et al. (2000) describe a study to demonstrate how applying appropriate ergonomic principles during design can reduce many life cycle costs.

Traditional methods for ergonomic analysis were based on statistical data obtained from previous studies or equations based on such studies. An ergonomics expert was required to interpret the situation, analyze and compare with existing data and suggest solutions. One such study is described by Sylvie Montreuil (2000), where an ergonomic group considered solutions to transform work situations during a brainstorming session and weighing of the solutions. The standard analytical tools included NIOSH lifting equation (Dempsey 2002), Ovaka posture analysis (Keyserling 2004), and Rapid Upper Limb Assessment (McAtamney and Corlett), among others.

Various commercial software systems are now available for ergonomic studies. Hanson (2000), presents a survey of three such tools, ANNIE-Ergoman, JACK, and RAMSIS, used for human simulation and ergonomic evaluation of car interiors. The tools are compared and the comparison shows that all three tools have excellent potential in evaluating car interiors ergonomically in the early design phase. Jack (UGS 2004), an ergonomics and human factors product, enables users to position bio-mechanically accurate digital humans of various sizes in virtual environments, assign them tasks and analyze their performance. Gill et al. (1998) provide an analysis of the Jack software to highlight the usefulness for applications in the manufacturing industry. Eynard et al. (2000), describe a methodology using Jack to generate and apply body typologies from anthropometric data of Italian population and compare the results with a global manikin. The study identified the importance of using accurate anthropometric data for ergonomic analysis. Sundin et al. (2000), present two case studies to highlight benefits of the use of Jack analysis, one in the design phase of a new Volvo bus and the other in the design phase of the Cupola, a European Space Agency (ESA) module for manned space flights for the International Space Station.

The idea of using immersive and non-immersive virtual environments in ergonomic studies has been described in the literature. One such tool is the VR ANTHROPOS (Anthropos 2004). It simulates the human body in the virtual environment realistically and in real-time. The importance of virtual humans in simulation and design has also been put forth by Badler (1997) & Hou (2000). Ford has been using the "Design for Ergonomics" virtual manufacturing process (Ergosolutions 2003) using Jack. The Ergonomic Design Technology Lab at Pohang Institute of Science and Technology is also involved in human modeling, design simulation, design evaluation in virtual environments and design optimization (Ergonomic Technology Lab 2004). The potential value of ergonomics analysis using virtual environments is discussed in detail by Wilson (1999).

3 APPROACH

This section discusses the details of the technologies and tools used for the integration and describes the formulation of the integrated system. These technologies include JACK, VADE, shared memory, inverse kinematics, Jack-Script, and Tcl/Tk packages.

3.1 Technologies and Tools Used

The "Virtual Assembly Design Environment" (VADE) (Jayaram et al. 1999, Wang et al. 2003), developed at Washington State University was used as the VR-based application for this study. VADE is a fully immersive, VR-based engineering application that allows engineers to plan, evaluate, and verify the assembly of mechanical systems. VADE includes all the capabilities of modern virtual reality software; i.e. it supports stereoscopic viewing, texture mapping, trackers and gloves, and physically based modeling. Other functionalities provided in VADE to assist in the assembly process planning include collision detection, sweep volume generation, CAD-VR bi-directional integration for design changes, crane simulation, etc. The significant features of VADE in the context of this integration are the object-oriented design of the immersive system, a fully parametric human model and plug-in nature of the tracking devices.

The ergonomic tool identified for use in this integration was "Jack". Jack is an ergonomics and human factors product that helps enterprises to improve the ergonomics of product designs and workplace tasks. This software enables users to position bio-mechanically accurate digital humans of various sizes in a virtual environment, assign them tasks, and then analyze their performance. It has various ergonomic analysis capabilities built-in, including:

- Lower Back Spinal Force Analysis,
- Strength Prediction,
- NIOSH Lifting Analysis,
- Rapid Upper Limb Assessment, and
- Fatigue/Recovery Time Analysis.

These analysis tools are used in Jack by first positioning the human model and then analyzing the posture for ergonomic issues. This means that, in order to evaluate a complete assembly process, the real person performing the assembly has to be watched by an ergonomics expert who first identifies potential problem areas/postures. Then these postures need to be modeled in Jack (or created in Jack using tracking devices supported by Jack) before the analysis can be performed. The analysis is thus "*static or discrete*" being limited to a finite set of postures being considered.

3.2 Formulation of Integrated System

The aim of the integration is to make the human model in Jack follow the motions of the human model in the immersive environment, which in turn is controlled by the data obtained from the tracking device attached to the real human. At the same time, the analysis modules in Jack need to monitor the posture during each frame automatically and provide analysis results when necessary. In order to make the Jack human model follow the immersive environment human model, we need to share the tracking device data. The integration is designed to be in real-time, so the human model position in Jack also is updated according to the movements of the real human. The ergonomic modules in Jack can then be used to analyze the posture of Jack human model, and hence really, that of the user going through the task in the immersive environment.

The overall concept of the proposed integrated system is illustrated in figure 2. Figure 2 demonstrates the integration of the ergonomic analysis functionality as a plug-in feature for the Virtual Assembly Design Environment. The data from the tracking device, which is used by VADE to position and orient the human model in the simulation, is shared with Jack™ and allows both to simultaneously control their individual human models. Another process running in parallel will monitor the Jack human model for ergonomic analysis and flag problems as they occur. This process uses the analysis modules of Jack.

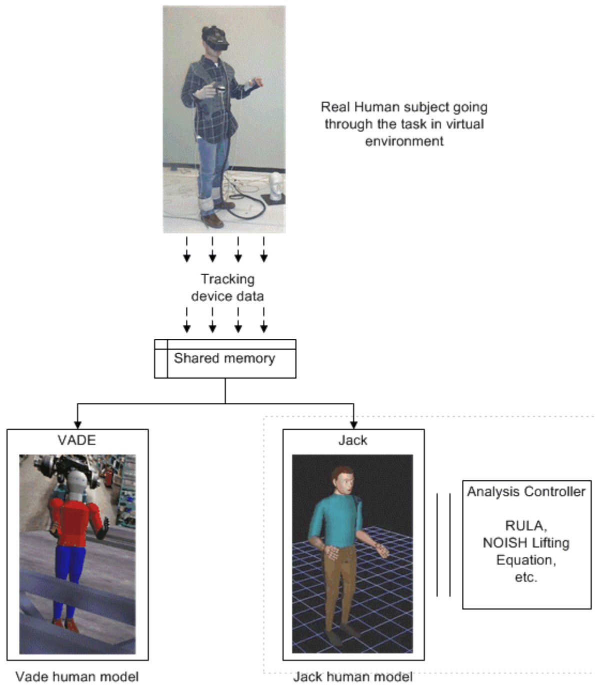

Figure 2: Integration Overview

There are three key modules which accomplish this integration:

- Data Communication module - Communication of VADE human model data to Jack,
- Human Coordination module - Application of VADE human data in Jack, and,
- Analysis Controller module – Controlling the Jack analysis module to check the posture every frame and report posture problems.

3.3 Human Coordination Module

In VADE, the tracking devices Flock of Birds (Ascension 2000) attached to the immersed user provides the location and orientation of the head, torso, and the upper and lower limbs of the real human. This data is mapped to the coordinate system of VADE to position and orient the VADE human model. As only six trackers are used in VADE, the position and orientation of other parts of the human model are calculated by using *inverse kinematics* algorithms. Details of the human model implementation in VADE can be obtained from Choi (2003). Thus, for the Jack human model to mimic the VADE human model, the complete human joint data in Jack needs to be synchronized with that of VADE.

We accomplished the data sharing using *shared memory*. Shared memory allows developers to create and access the same segment of memory from multiple processes. This enables the processes to communicate efficiently and reliably with each other and is the fastest mode of Interprocess communication (IPC).

In VADE, the locations and orientations of the various body segments are calculated. However, the joint angles need to be calculated for Jack (explained later). The Data Communication Module gets the position and orientation of the trackers from the tracking device and sends it to shared memory. VADE calculates the locations and orientations of all the other body parts using inverse kinematic analysis to update the VADE human model. The Jack Human Coordination Module, calculates the joint angles from the shared memory data (explained in Section 4).

3.4 Human Coordination Module

JackScript, the python-based application programming interface (API) to Jack, was used to position and orientation the Jack human model. It is an object-oriented scripting system and wraps basic functionality within the core of the application and allows for useful extensions to the basic functionalities.

This module performed two functions to achieve the coordination:

- Read data from shared memory: The shared memory was accessed using Python/C API (Python/C API Reference Manual, 2002), which allows developers to write modules in C or C++ to extend the Python interpreter with new modules. The module was compiled into a shared library and used in Jack to access the memory segment created by the Data Communication Module.
- Update the Jack human model: The values obtained from shared memory are used to calculate the joint angles which are then verified for the maximum and minimum limits of corresponding values for joints (using the API function joint.GetLimits) in Jack. This module then controls the human model in Jack by calling a series of 'set' functions, which set the joint angles of the Jack human model according to the data obtained from shared memory. This data needed to be mapped to the Jack coordinate system before being applied.

This script forms the "VadeExt" module and performs the task in a continuous loop. Thus it updates the position and orientation of the Jack human model in every frame of the simulation. This module is used by the Analysis Controller (described next) and the corresponding analysis is performed.

3.5 Analysis Controller Module

The Analysis Controller monitors the motion of the Jack human model continuously and performs the ergonomic analysis of the posture during the simulation.

The calls to analysis tools are not implemented in Jack's Python-API. Earlier scripting/extension mechanisms in Jack had been built using Tcl scripts. Jack provides a convenient way of packaging and sharing scripts and tools developed as sets of add-on tools, or *modules*. This mechanism is based on Tcl *packages* and has been extended with hooks for menu creation and other types of module initialization tasks in Jack.

Different modules can be developed for using different analysis tools available in Jack. The VadeExt module described in the previous section remains the common component for the integration that controls the human model. For each ergonomic analysis tool, we first need to call the 'VadeExt' module and then make the API calls to activate and record the analysis. Figure 3 shows the flowchart of the Analysis Controller.

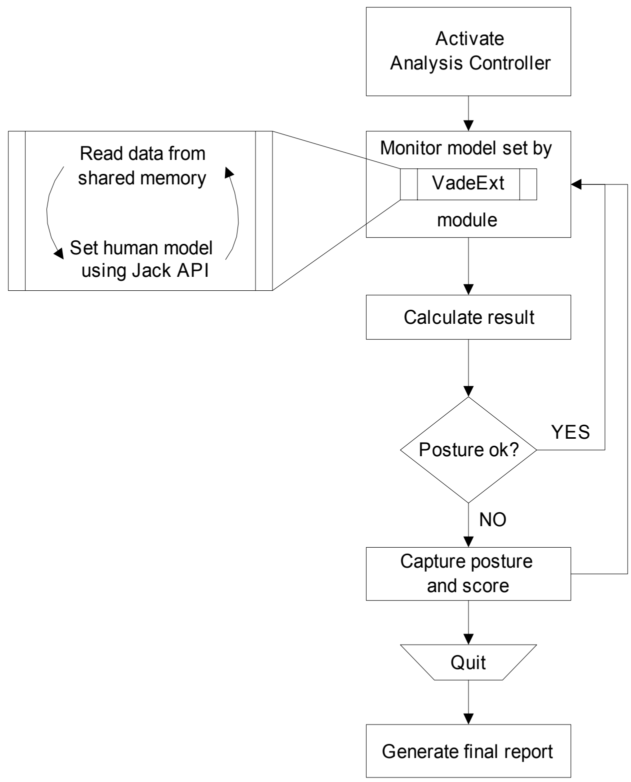

Figure 3: Algorithm for Analysis Controller

The monitoring system continuously analyzes the human model and if a potentially unsafe posture or condition is detected it generates a report automatically. Jack's built-in report generator module is invoked for this purpose and modified to generate a customized report for this integrated application.

4 DISCUSSION OF INTEGRATION ISSUES

4.1 Synchronizing Human Models

The "VadeExt" module is responsible for positioning and orienting the Jack human model and the associated body segments. Multiple approaches can be taken to use the data obtained from the tracking device to make the human model follow the immersed user's motion because of the various API functions supported by Jack.

The human synchronization necessitates the modification of all the joint angles in Jack. If we consider the upper limb, to modify all the joint angles, we would either have to use more trackers to get location and orientation on the upper arm, lower arm and wrist, or create a custom inverse kinematics module to calculate these parameters, or use the VADE inverse kinematics to calculate the joint angles and then supply them to Jack.

Our approach was to use the inverse kinematic functionality built into Jack. The "ReachHold" function provided by the Jack API calculates the upper arm position using its own inverse kinematics algorithms. It takes a goal in space and orients the upper limb so the human model reaches for that point in space. By default, the palm center on the human model's hand is used to reach the specified point in space. There are three issues of concern in this approach:

- The inverse kinematics of VADE and those of Jack could yield slightly different results. Since VADE used the location of the forearm from a tracker and only calculated the location of the upper arm through inverse kinematics, the solution is unique and represents accurately the actual human posture. Since Jack was using only a point to reach for with the palm, there could be differences in the combination of the wrist, forearm, and upper arm that can reach the same point. However, Jack uses the most "comfortable posture" while performing a reach. Thus, in cases where the operator is performing reasonably comfortable tasks, the differences should not exist. In order to test this, the motions of the human model were simulated and compared to make sure that there are no significant difference in the final position of the palm as calculated by VADE's and JACK's inverse kinematics algorithms.
- These calculations in Jack create an overhead to some extent and cause a slight lag in the response of Jack to changing tracking data.
- Since the operator has the tracking device attached to the wrist, if we provide the raw tracker data as a reach-for point, the orientation of the upper arm will offset the real hand position. Figure 4 illustrates the problem. Hence an offset was added to the tracking device data in order to provide Jack with the location of the palm calculated from the tracker data and hand size.

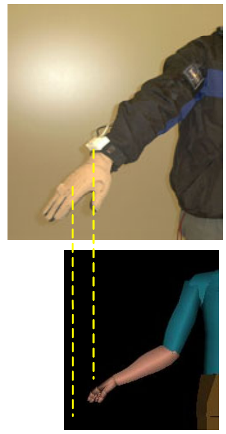

Figure 4: Offset Required for 'ReachHold' Function

4.2 Human Model Calibration

Another important issue relates to the calibration of the human model. The VADE human model used was created as a 50th percentile human. But a person with a different size and shape can be immersed in the environment. VADE allows us to set 13 parameters (for the human body) in a data file and connect to the CAD system to generate different sizes of the human model. Jack also allows a segment by segment modification of the human model. If multiple people are used in this integrated environments, methods need to be implemented to use this parameter data file to generate the human model in JACK also. This will ensure that the two human models in VADE and JACK are the same in terms of segment sizes.

5 DEMONSTRATOR IMPLEMENTATION

The proposed integration was implemented on an Onyx2 system with six processors. A V-8 helmet, CyberGlove and Flock of Birds hardware devices were used for the virtual assembly application.

A prototype was implemented using a scenario from an industry partner to demonstrate the application of this integration and to test the validity of the proposed system. The case study involves simulation of manufacturing a sheet metal component on a press machine to evaluate the task process for upper limb injuries. The Rapid Upper limb Assessment tool (McAtamney and Corlett, 1993) available in Jack was used for the purpose. This analysis evaluates a posture and rates it on a scale of one to seven, one being most comfortable. Factors that affect this analysis include the posture, weight of part, repetitions, etc.

The virtual environment generated for the simulation is shown in Figure 5. It shows the press machine with bins

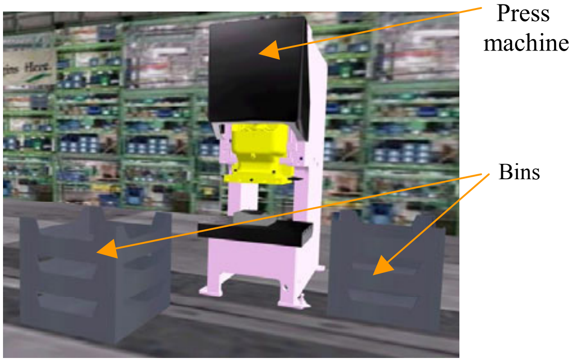

Figure 5: Virtual Environment for the Simulation

around it from where the raw material will be picked up and loaded on to the press machine.

The task involved placing the blank piece on the die. The user then initiates the stroke by pressing a switch on the machine panel. Figures 6 (a) and 6 (b) show the first task of placing the blank piece on the press machine. The human model in Jack followed the motions of the immersed user. The RULA analysis module showed a maximum score of 5 for this activity.

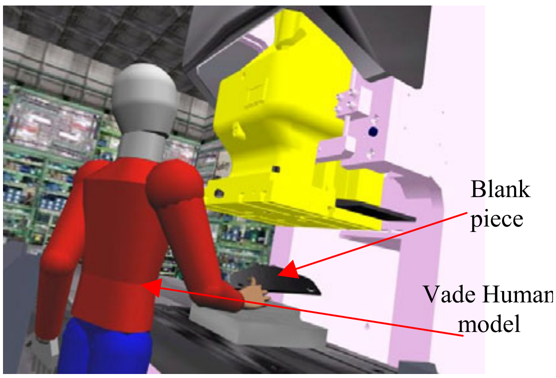

Figure 6(a): Human Model in Immersive Environment Placing the Blank on the Press Machine

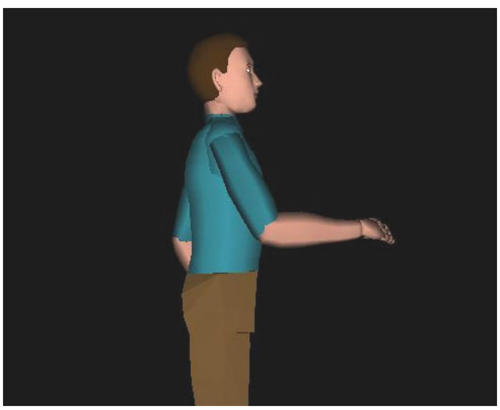

Figure 6(b): Human Model in Jack Following the VADE Human Model

Figures 7(a) and 7(b) show the task of reaching out for the switch to start the stroke for the press machine.

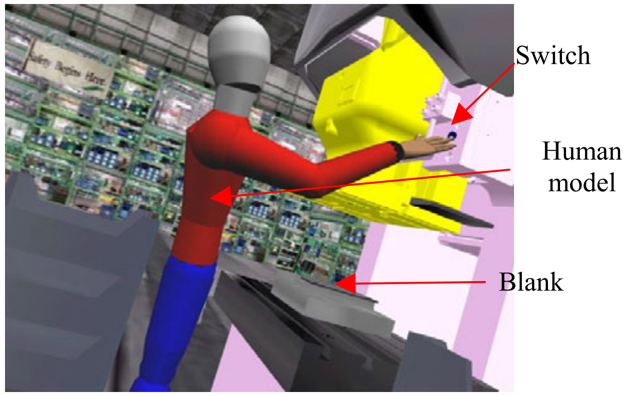

Figure 7(a): Human Model in Immersive Environment Reaches out for the Switch of the Press Machine

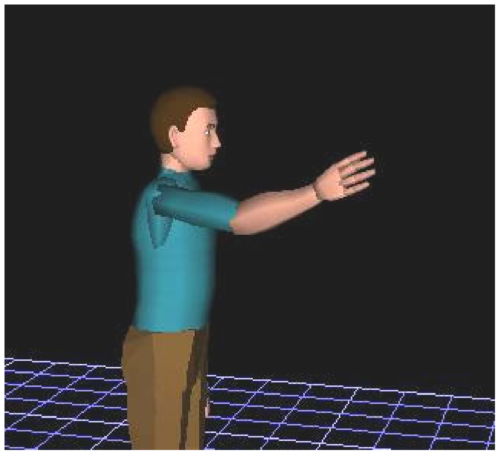

Figure 7(b): Human Model in Jack Reaches out for the Switch of the Press Machine

The RULA module reported a high score of seven for this activity, suggesting that immediate revisions are required in this process. Further analysis showed that the primary reasons for the high score were the high location of the button and the repetitive nature of the task of pushing the button. We experimented with a small platform on which the worker could stand and operate the switch. The RULA score reported in that case was 5, which was a considerable improvement.

Figure 8 shows the RULA user interface in JACK where the user can modify the parameters such as “Muscle use”, “repetition” etc. in real-time as the JACK human model follows the immersed user’s motions. Changing these parameters will update the score reported in real-time as the “updateScore()” function is called during every frame of the simulation.

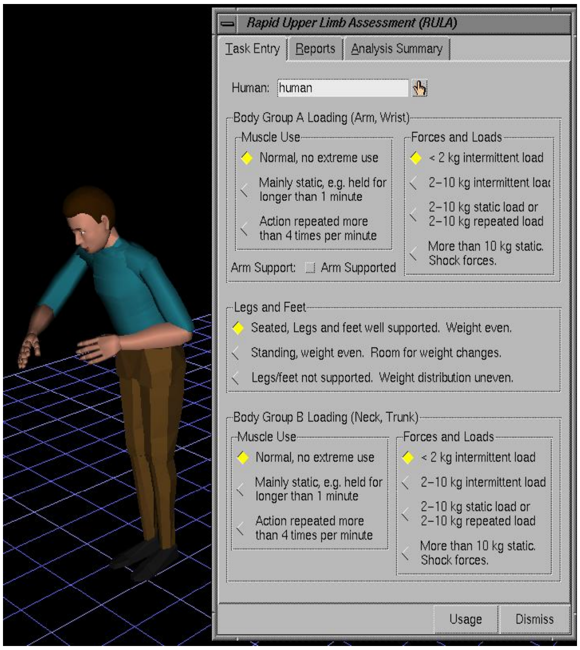

Figure 8: RULA GUI to Change Parameters

6 COMPARISON WITH JACK'S MOTION CAPTURE TOOLKIT

Jack provides a Motion Capture Toolkit to configure and use virtual reality (VR) devices. A menu based interface allows configuration of the sensors. This direct connection of tracking device will help in simulating the human model. However, it was observed that loading of the entire virtual environment in Jack slows down the application significantly. A feeling of immersion is attained only when the entire surrounding environment is loaded, including the work station, parts involved, tools used, bins, fixtures and other objects in the environment. Therefore, the real-time immersive VR evaluation performance of Jack was deemed to be inadequate by itself. Jack's main functionality of ergonomic analysis tools can be better utilized with another application whose main functionality is to provide the capability for immersed visualization. Thus, the two applications, VADE and Jack, can be used concurrently to leverage the functionality strengths of each, without inducing significant overhead in either application.

7 CONCLUSION

The integration of Jack ergonomics analysis functionality with the virtual assembly system illustrates the methodology for enhancement of the functionality of an immersive system through integration with a commercial ergonomics analysis tool. This also enhances the functionality of Jack by providing a dynamic analysis of the posture, which is not available today in the commercial product. The ergonomic analysis extension of the immersive system will aid in improving productivity and quality of products by designing better workplaces and developing optimized product development cycles. Participatory ergonomics will further help in better training of the workers.

Reliable and accurate data sharing is significant for such integrations. Based on the basic data sharing presented in this work, more detailed data can be sent across, either from Jack to VADE or vice-versa, to further enhance the integration framework. As an example, since Jack is a tool that specializes in human modeling, the position and orientation of VADE human model can be controlled by using data from Jack human model. In future implementations, CORBA or .NET can be used as middleware to allow cross-platform integration instead of using just shared memory data.

This integration offers a prototype for further integration of other CAE tools to add more functionality to VR-based applications. Since many immersive visualization systems are custom developed and the interactions required vary largely based on the application, it is important that the flexibility of these customized tools not be compromised because of certain analysis capabilities that are required in the application. The integration approach presented in this paper allows these custom developed applications to integrate external analysis software and provide a more useful tool to the engineering community. This technology and the implementation illustrate the advantages of using off-the shelf software in an integrated environment combining advanced visualization systems, human modeling systems, and CAD/CAM systems, rather than reinventing the wheel.

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