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Jack Human Modelling Tool: A Review

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ABSTRACT

When evaluating the design of a workstation human factors practitioners have traditionally used a number of different approaches to assess the design, including two-dimensional drafting mannequins and physical mock ups. In the late 1960s, human modelling software became available, and aerospace and automotive manufacturers saw the potential for much of the design process to take place in a virtual environment. Modern human modelling tools include Jack and Ramsis. As part of Project MIS 872, the Defence Science and Technology Organisation was supplied with a copy of Jack. This report serves as a review of the base Jack tool (version 5.1), with specific focus on the features relevant to the assessment of seated workstations.

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Executive Summary

When evaluating the design of a workstation human factors practitioners have traditionally used a number of different approaches. During the initial stages of the design process, the workstation drawings would be evaluated using two-dimensional drafting mannequins. At a later stage in the design process, a mock up of the workstation would be constructed and the design would be assessed using anthropometric dummies or “live” test subjects. In the early 1960s computer aided design (CAD) software became available, and aerospace and automotive manufacturers saw the potential for much of the design process to take place in a virtual environment. Recognising the potential to accelerate the design process and at the same time optimise the human machine interface, digital human modelling tools emerged in the late 1960s. Human modelling software is now widely used in the defence, automotive and manufacturing industries.

Modern human modelling tools in common use today include Jack and Ramsis. As part of Project MIS 872, the Defence Science and Technology Organisation was supplied with a copy of the Jack software so a human modelling capability could be developed. Development of the Jack tool began in the mid 1980s at the University of Pennsylvania, with significant financial support provided by the US Army. Following the commercialisation of Jack, it is now developed and marketed by Siemens. The Jack model of the human has a complex kinematic linkage system that closely resembles the human skeletal structure, joints that obey physiological range of motion restrictions and a geometric shell that closely resembles the human shape. Human models can be created based on data from recent comprehensive anthropometric surveys, as well as by specifying up to 26 individual anthropometric dimensions, including stature, sitting height, and buttock-knee length. A range of behavioural controls can be specified, allowing the movement of the human to be constrained based on the selected behaviour. Jack provides the user with the ability to create virtual workspaces using its own CAD modelling tools and library of objects ranging from basic shapes to office chairs and ladders. In addition, workspaces can be imported in numerous formats using third-party translators. A range of human factors analysis tools are available, including the graphical display of reach zones and field of view. This report serves as a review of the base Jack tool (version 5.1), with specific focus on the features relevant to the assessment of seated workstations.

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1. Introduction

1.1 Traditional Workspace Evaluation

Traditionally, when evaluating the design of a workspace, human factors practitioners have used a number of different approaches. During the initial stages of the design process, this would involve the assessment of the workspace drawings using two-dimensional drafting mannequins. Usually, these articulated mannequins represent a side-on view of the human, although plan view and fore-aft view mannequins have also been used [1]. The transparent mannequins, which usually represent 5th and 95th percentile statures, are overlaid on the drawings and assessed for accommodation, ensuring the mannequins have the appropriate field of view, can reach all the controls, and have clearance with the workplace structures.

At a later stage in the design process, a mock up of the workspace would be constructed and the design would be assessed using anthropometric mannequins (such as the Society of Automotive Engineers J826B H-Point mannequin) or “live” test subjects [2]. If any problems were encountered with the design alterations would have to be made to the mock up, or a completely new mock up would have to be constructed. The development of a number of mock ups during the design process can be very costly and time consuming. For example, during the development of a new car model many mock ups have traditionally been constructed, the mock ups costing between US\$500,000 and US\$1,000,000 [3]. Another problem in assessing the design of a mock up is ensuring the availability of a sufficient number of “live” subjects or dummies which are representative of the anthropometrically “hard to fit” members of a population (typically about 30 subjects are used in cockpit accommodation studies [4]).

1.2 Digital Human Modelling

1.2.1 History

In the early 1960s computer aided design (CAD) software became available [5], and aerospace and automotive manufacturers saw the potential for much of the design process to take place in a virtual environment. The development of CAD modelling software meant that designs could be created on a greatly reduced timescale, while at the same time allowing for the exploration of a wider range of design solutions [6]. Recognising the potential to accelerate the design process and at the same time optimise the human machine interface, digital human modelling tools emerged in the late 1960s in the automotive and aviation industries [7].

First Man, widely reported as the first human modelling tool, was developed by the Boeing company in the late 1960s to assess pilot accommodation in aircraft cockpits and later became known as Boeman [6]. The Boeman mannequin, shown in Figure 1, had 23 joints and its size was based on anthropometric data for a 50th percentile man [5]. The segment lengths could be scaled to any dimension, although the depth and breadth of the segments could not be changed. The program was written in FORTRAN IV and ran on a CDC 6600 computer. The input describing the mannequin and environment was entered in batch mode and the output was displayed on a plotter as graphics capable terminals were not common in the late 1960s.

The Boeman software was developed further for military aircraft design and evaluation [8] and evolved into the Computerised Biomechanical Man Model (Combiman), shown in Figure 2. Combiman was developed at the University of Dayton and further development took place at the Armstrong Aerospace Medical Research Laboratory [8]. Using Combiman, a mannequin could be created based on anthropometric data from six military databases. Alternatively, a mannequin could be created by specifying 12 body dimensions [7]. To support ergonomic analysis, Combiman could produce field of view plots and determine the reach of the pilot, taking into account the effect of clothing and harnesses [6]. Furthermore, strength predictions could be made based on empirical data.

In addition to the aviation environment, models have been developed to assist automotive design since the 1970s. One of the first was the Cybernetic man-model (Cyberman), shown in Figure 3, which was developed in the 1970s by the Chrysler Corporation for the in house design and evaluation of automobiles [7]. The mannequin was made up of 15 segments of any required size, but the mannequin did not have joint constraints, so care had to be taken when posing the mannequin [5].

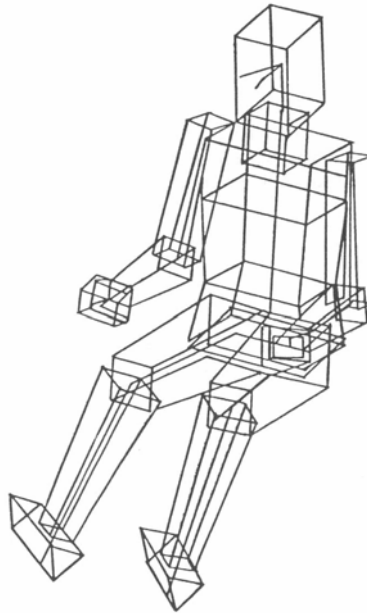


Figure 1: The Boeman model (reproduced with permission [8], ©IEEE)

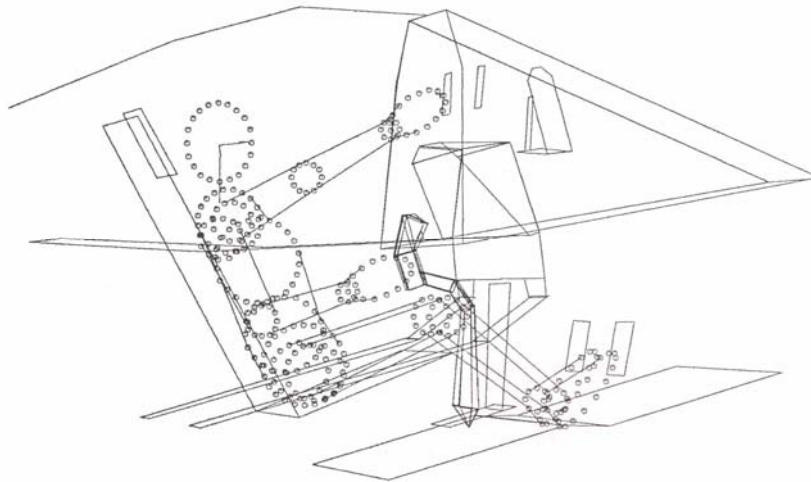


Figure 2: *The Combiman model reaching for a control in a cockpit (reproduced with permission [8], © IEEE)*

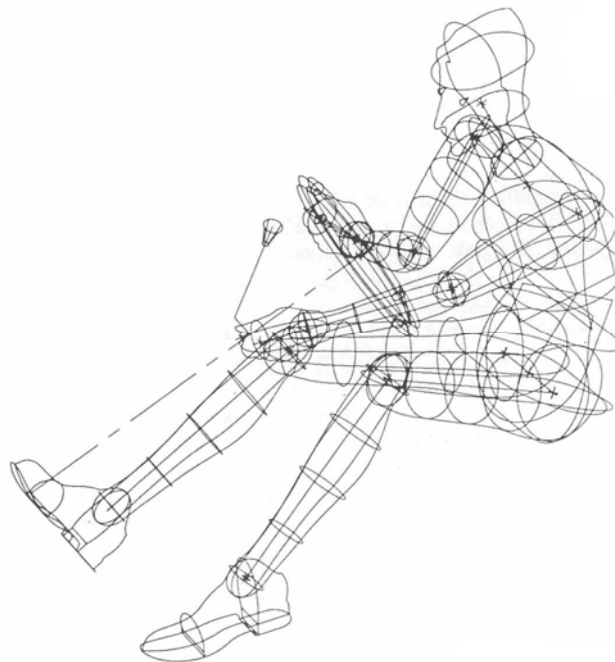


Figure 3: *The Cyberman model developed by the Chrysler Corporation (reproduced with permission [8], © IEEE)*

Following the development of models like Boeman in the late 1960s, a large number of human modelling tools with a range of applications have been developed. A survey of human modelling tools in 1985 [5] reviewed about 30 models that had a diverse range of uses, such as cockpit accommodation analysis and the modelling of humans in automotive accidents. With the increasing power of computers, the capabilities of modern human modelling tools have increased dramatically compared to their predecessors developed in the 1960s and 1970s, such as Boeman and Cyberman. The widely used modern tools used for ergonomic analysis are described below.

1.2.2 Modern Human Modelling Tools

1.2.2.1 MannequinPro

MannequinPro, shown in Figure 4, is a PC based human modelling tool available since 1990. The model is pitched at the bottom end of the market and is priced around US\$1000 [9]. MannequinPro can create male and female models based on 11 anthropometric survey populations, including data from the US Army and the National Aeronautics and Space Administration (NASA). Mannequins can be created based on a range of percentile statures from 2.5 to 97.5 percent. In addition, the mannequin's joints have a realistic range of motion. A range of ergonomic assessment tools are available, such as the graphical display of field of view and reach envelopes, along with the ability to calculate joint forces. MannequinPro was used by Air Operations Division in the late 1990s to assist in the evaluation of pilot and loadmaster field of view in a S-70A-9 Black Hawk helicopter [10].

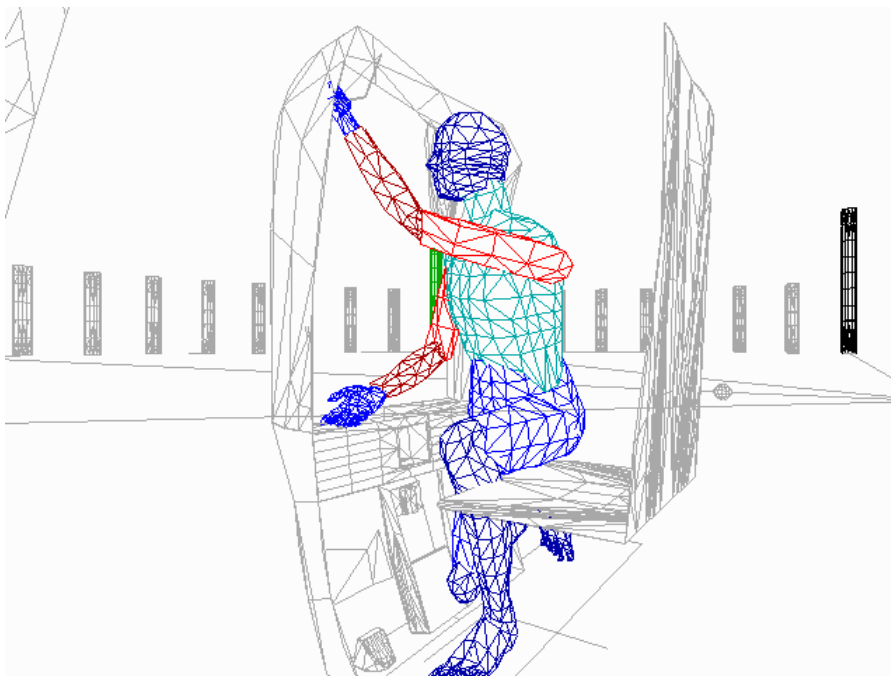


Figure 4: A MannequinPro mannequin in a typical posture used by Australian Army Black Hawk helicopter loadmasters

At the higher end of the market a range of powerful and expensive human modelling tools are available.

1.2.2.2 Jack

The Jack human modelling tool (originally called Tempus) was developed at the Centre for Human Modelling and Simulation at the University of Pennsylvania in the mid 1980s by a team led by Dr Norman Badler [11]. The main impetus for the development of Jack was to support the design and development of workspaces, with the emphasis on optimising the human machine interface. Funding for the development of Jack came from a number of sources, including significant support from NASA and the US Army. Jack is used across a

broad range of industries by companies and organisations such as John Deere, BAe Systems, NASA and the US Army¹.

1.2.2.3 *RAMSIS*

The realistic anthropological mathematical system for interior comfort simulation (RAMSIS) model was developed in the late 1980s. It was developed as a co-operative arrangement between German automobile manufactures, Tecmath and the Technical University of Munich, Germany [12]. RAMSIS is used extensively in the automotive industry for the design of vehicle interiors and exteriors, by companies such as Audi, Volkswagen, Daewoo, Ford, Honda, Mazda and Renault². In the Australian automotive industry, Ford Australia has used RAMSIS for a number of years, the tool being extensively used during the development of the BA Falcon³.

1.2.2.4 *Safework*

Safework is also widely used in the automotive, manufacturing and defence industries by companies such as General Dynamics, Daimler Chrysler and Boeing, and government organisations like Defence Research and Development Canada⁴. Safework was originally developed at the Ecole Polytechnique, Canada, in the 1980s and is now developed by Dassault Systemes [12].

1.2.2.5 *SAMMIE*

The system for aiding man-machine interactive evaluation (SAMMIE) was originally developed at the University of Nottingham and subsequently at Loughborough University [6]. The model has been applied to a diverse range of problems in areas such as tram driver workstation and aircraft cockpit design.

These tools have human models that have complex kinematic linkages that closely resemble the human skeletal structure, joints that obey physiological range of motion restrictions and a geometric shell that closely resembles the human shape [13]. Models of the human can be created based on recent comprehensive military and civilian anthropometric surveys. In fact, Safework allows the specification of over 100 anthropometric variables, including foot length, buttock-knee length, stature and span [14]. Workspaces can be created and modified using a range of native CAD modelling tools along with libraries of standard objects, such as office furniture. Alternatively, workspaces can be imported from third party CAD software packages. A range of human factors analysis tools are available to support the assessment of a workplace. For example, reach envelopes can be generated and collision detection algorithms can be used to determine if a task can be completed safely.

¹ Source: Ulrich Raschke, Siemens

² Source: www.ramsis.de

³ Source: Roger Lewis, Ford Australia

⁴ Source: Eric Coutu, Safework.

1.2.3 Human Modelling Case Studies

Human modelling tools have been successfully applied across a diverse range of problems, from determining the grip height for a weed trimmer, to the design of the International Space Station [3]. Two examples of the uses of human modelling tools are presented in depth below.

1.2.3.1 Tram Driver Workstation Design

SAMMIE was used to investigate a number of design issues for the STIB Tramway 2000 tram project [6]. In particular, entry into the driver workstation and the design of the workstation itself were identified as potential ergonomic issues. Initially, a detailed CAD model of the tram (including both the driver workstation and passenger compartment), shown in Figure 5, was constructed from engineering drawings supplied by the company and imported into SAMMIE. Anthropometrically accurate virtual tram drivers were created from data supplied by STIB. In addition, models of passengers were created based on published data for Europeans. Evaluation of driver ingress into their workstation determined that the drivers did not have easy access to the workstation due to the width of the door and low height of the ceiling. Furthermore, it was also found that a high ingress step and very limited standing space just inside the driver's door compounded the difficulty the drivers experienced getting into the workstation. Based on this evaluation, a number of modifications were proposed to improve driver ingress, including changes to the ceiling height and rear-wall cupboard. The driver workstation had a wrap-around design, enabling the driver to reach all the controls and also allow the driver to rotate their seat (so they faced the rear of the tram) and sell tickets to the boarding passengers. Using a range of mannequin sizes (from small females to large males), the wrap-around driver's console was analysed. Using these mannequins, the console height, position of the tram controls and the range of seat positions required were determined. In addition, the need for an adjustable footrest was also identified to accommodate the smaller drivers. It was determined that the drivers would have difficulty performing both the driving and ticket selling tasks. A design was proposed that compromised between the requirement to rotate the seat to sell tickets and drive the tram. The solution, which didn't require major changes to the tram, allowed the seat to both translate and rotate to enable the driver to complete both tasks comfortably. Lastly, using the SAMMIE mirror modelling capability, it was also determined that the full range of drivers had adequate view of passengers entering and leaving the tram.

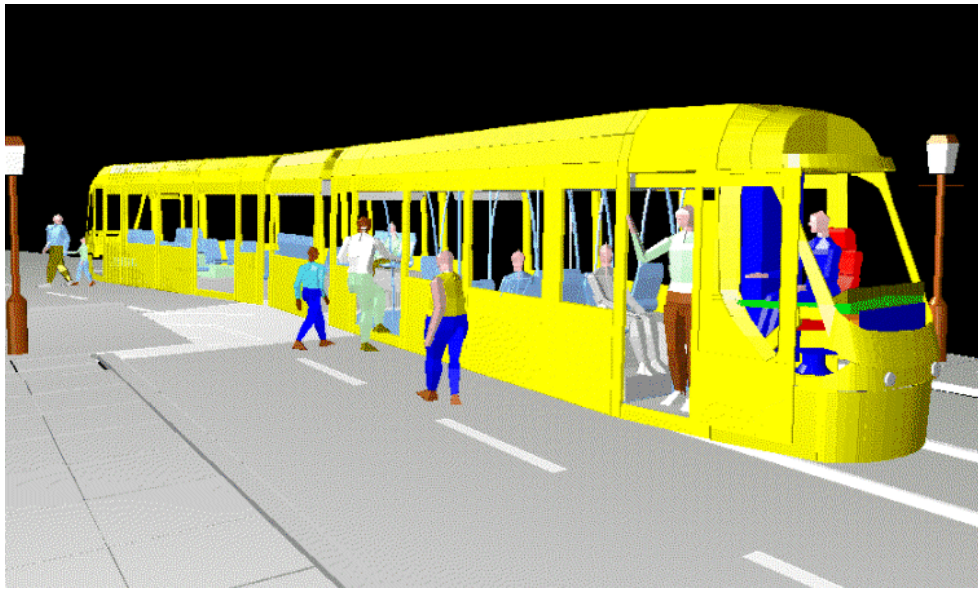


Figure 5: A model of the tram in SAMMIE complete with driver and passengers (reproduced with permission)

1.2.3.2 Comanche Helicopter Redesign

One example where human modelling has been applied in a military context is the RAH-66 Comanche helicopter redesign [15]. The Comanche is a two crew attack helicopter developed as a replacement for the AH-1 Cobra and OH-58 Kiowa Scout (the project was cancelled in 2004). Originally, this helicopter was required to accommodate anthropometrically the central 90% of the US Army male population. Following a policy change in 1993 that allowed females to fly combat aircraft, the helicopter was then required to accommodate the central 90% of both male and female US Army personnel. In addition, new life support equipment was also going to be fitted, which would affect the percentage of people accommodated. Because of the difficulty gaining access to the two prototype aircraft and coordinating people who represented the appropriate extremes in body size it was decided to take a human modelling approach (Figure 6) using Jack to determine the changes required to the aircraft.

Using the principal component analysis technique [16], boundary mannequins were created that represented the anthropometric extremes of the population to be accommodated. Furthermore, a comprehensive range of aircrew clothing and equipment, including helmets, combat boots and life preservers were digitised and placed on the mannequin. To correctly position the mannequin in the CAD model of the helicopter, real subjects were placed in the prototype cockpit and key landmarks were digitised on their bodies. The mannequins were then positioned in the cockpit based on these landmarks. A number of accommodation criteria were identified for the Comanche that each pilot would have to meet, including external and internal field of view, clearance with controls and aircraft structures and reach to controls. Following an accommodation analysis, seven design modifications were recommended to accommodate the target population, including changing the seat design to allow fore/aft adjustment of the seat as well as vertical adjustment.



Figure 6 A clothed and equipped Jack mannequin in the Comanche helicopter (reproduced with permission)

1.3 Summary

Since the late 1960s human modelling tools have played an increasing role in the automotive, aviation, manufacturing and defence industries. The mannequins have evolved from a simple arrangement of shapes that approximate a human to a complex kinematic linkage system that closely resembles the human skeletal structure, joints that obey physiological range of motion restrictions and a geometric shell that closely resembles the human shape. Furthermore, each package offers a range of tools that can be used to conduct an ergonomic assessment. Human modelling tools have played a key role in numerous projects, including the development of the International Space Station and the redesign of the Comanche helicopter. As part of Project MIS 872 Aircrew and Crewstation Anthropometry, the Defence Science and Technology Organisation was provided with a copy of the human modelling tool Jack. This report describes the capabilities of the Jack base tool (version 5.1).

2. Jack

2.1 Background

Development of the powerful Jack human modelling tool began in the mid 1980s at the Centre for Human Modelling and Simulation at the University of Pennsylvania [20]. The main impetus for the development of Jack was to support the design and development of workspaces, with the emphasis on optimising the human machine interface for the specified population. Funding for the development of Jack came from a number of sources, including significant support from NASA and the US Army. Following the commercialisation of Jack, it is now developed and marketed by Siemens.

Over the past two decades the Jack representation of a human has evolved from a simple, unrealistic arrangement of tetrahedra (Figure 7) to a highly realistic human model based on current anthropometric, anatomical and biomechanical data (Figure 13). To support human factors analysis, humans can be created based on recent comprehensive anthropometric surveys, as well as by specifying up to 26 individual dimensions of a person, including stature, sitting height, and buttock-knee length. The Jack mannequin has a complex kinematic linkage model that closely resembles the human skeletal structure, joints that obey physiological range of motion restrictions and a geometric shell that closely resembles the human shape. The mannequins have complex models of the spine and shoulders based on inverse kinematic algorithms that ensure that the body moves in a realistic fashion. The humans can be posed using an extensive posture library. Furthermore, a range of behavioural controls can be specified, allowing the movement of the human to be constrained based on the selected behaviours. For example, requiring a pilot's hand to maintain contact with a helicopter collective throughout its range of motion. Jack provides the user with the ability to create virtual workspaces using its own CAD modelling capability and library of objects ranging from basic shapes to office chairs and ladders, or workspaces can be imported in numerous formats using third party translators. A range of human factors analysis tools are available to support the assessment of a workplace. For example, reach envelopes can be generated and collision detection algorithms can be used to determine if a task can be completed unhindered.

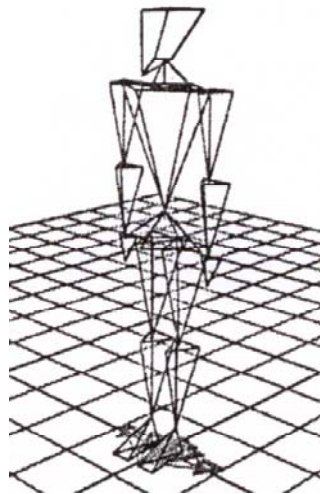


Figure 7: An image of the Jack model from the late 1980s (used with permission)

2.2 Jack Structure

At the highest level, a scene in Jack, which can be composed of one or more objects that make up the workspace and humans who work in it, is referred to as an environment (Figure 8). At the next lowest level, the objects and humans that populate the scene are referred to as figures. Figures can be an anthropometrically realistic articulated model of a male or female human or an object such as an office workstation, aircraft cockpit, or a simple structure such as a cube. Figures are represented in Jack by a simple polygonal geometry made up of a number of flat surfaces, usually triangular faces, with each face defined by joining three or more points

(nodes). Figures can range in size from a handful of polygons for a simple object (such as a cube), up to hundreds of thousands of polygons for a complex object like an aircraft. The lowest level in the Jack structure is the segment, which is joined to other segments by joints to form an articulated figure. The information describing an environment is contained in an environment file, which contains all the information needed to recreate a scene. Environment (.env) files include information describing the figures (humans and objects), segments (the building blocks of the figures), relative locations of the figures, and their joint angles and positions, along with geometry scaling, constraints and attachment information. The description of a figure, including the segments, joints, sites and segment colours are included in a figure (.fig) file. The data describing the segment geometry are contained in a polysurface (.pss) file.

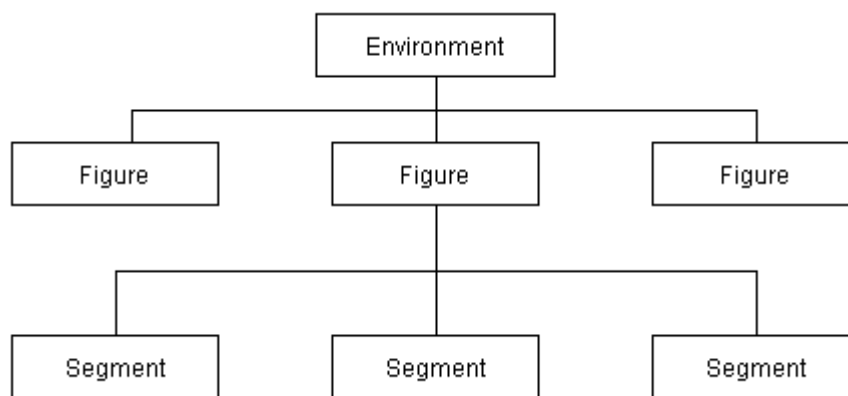


Figure 8: The Jack hierarchy

2.3 Graphical User Interface

The Jack graphical environment is composed of two elements. Firstly, a control bar, shown in Figure 9, that by default is located at the top of the screen. The control bar is composed of several elements, including a series of pull-down menus for the creation and editing of objects and humans, along with tools for the analysis of the workplace, and help. Directly below this is a number of icons providing shortcuts to commonly used commands, including icons to zoom, move a figure, scale a human, adjust a figure's joint, and add behavioural constraints to a human. Directly below the row of icons is message area that provides feedback on the current operation (indicating the status of a file importation, for example). To the right of the icons is the move controller, allowing the selected item to be moved (in either local or global co-ordinates). In addition to the control bar, by default one graphical window (labelled "TJ_Window", a legacy of the original commercial developer Transom) is also displayed that shows a view of the Jack environment (Figure 10). As required, extra graphics windows can be added to provide different views of the environment.



Figure 9: The Jack control bar

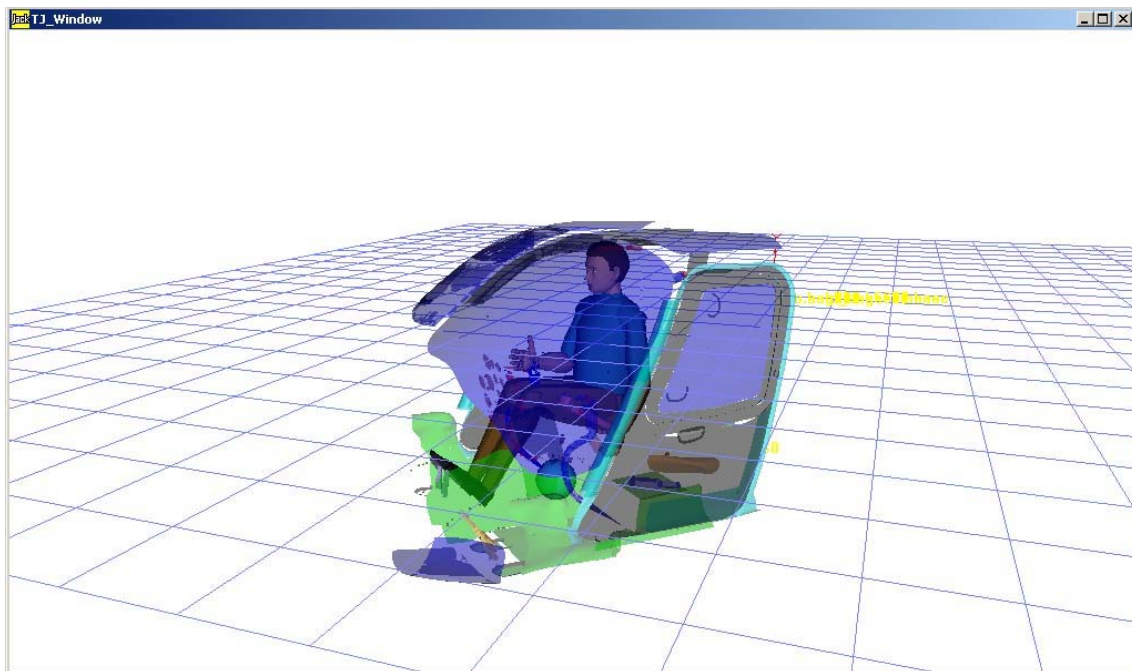


Figure 10: The Jack graphics window showing a Kiowa helicopter model and a mannequin

3. CAD Modelling

The first step in the ergonomic evaluation of a workplace is the creation of a virtual model of the workplace in the Jack environment. A workplace can be developed using Jack's in built CAD modelling tools or a CAD model of the workplace can be imported in a wide range of formats. This section describes the options available for the importation, creation and editing of CAD models.

3.1 CAD Modelling Tools

Jack can create a range of simple CAD objects using its native modelling capability, such as a sphere, cone, cylinder, or cube, which can be used as building blocks to create more complex structures. In addition, Jack has a library of objects (office furniture, for example), which can also be used to construct a workplace (Figure 11). Various options are available to edit these objects, including the ability to scale the object in one or more dimensions. In addition, nodes (points defining a face) and faces can be removed, repositioned or added. Also, the segments that make up an object can be merged or split. Three options are available for the display of an object, shown in Figure 12, shaded, wireframe and transparent. To augment the realism of the objects, texture maps can be added to the faces of objects, so an image of an instrument panel can be added to a model of a helicopter cockpit, for example.

Articulated objects can be constructed by creating a joint between two segments. So, for example, a cockpit door of an aircraft can be opened and closed to examine ingress and egress. Up to six degrees of freedom can be defined for each joint, allowing rotation and translation

about the three axes. Upper and lower limits can be specified for each degree of freedom, either as an angular range or displacement. In addition, a resting position can be specified for each degree of freedom. Motors can also be added to a joint, allowing the joint to be continually exercised through its full range of motion.

Any serious development or editing of a CAD file, such as an aircraft cockpit, would require another product specifically designed for the task. While products like Safework can be embedded within high-end CAD packages like the computer aided three dimensional interactive application (CATIA), they are also considerably more expensive. While Jack itself has limited CAD creation and editing capabilities, a number of different CAD file formats can be imported into Jack. This capability is described in the next section.



Figure 11: An example of some of the objects available in the Jack library

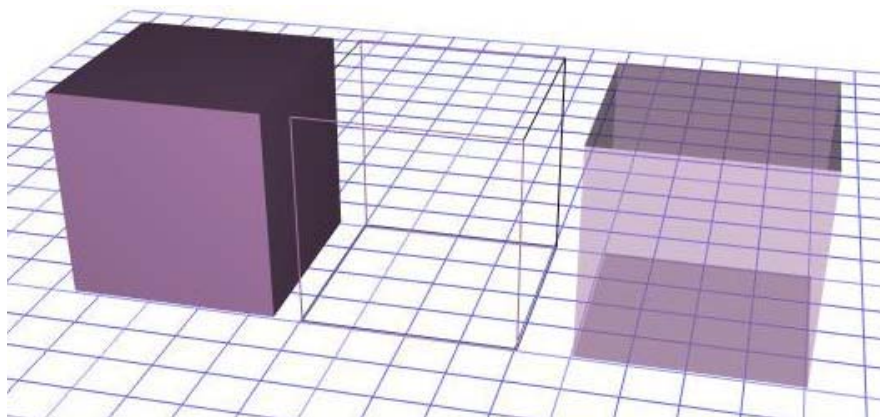


Figure 12: The three options for displaying an object: shaded, wireframe and transparent

3.2 Importing CAD Models

A range of file formats, listed in Table 1, can be imported into the Jack environment. Although, it should be noted that the Jack user manual provides limited description of the importation options available, however the online help contains a link to a PDF document describing all the options available. At this time, we only have experience importing files in either the IGES 5.3 or VRML formats. Each file format has its own third party translator software associated with it that converts the file into the native Jack format. Jack gives the user a number of options when importing a model (depending on the file type being imported), such as the position and orientation of the object, whether to display lines and points, or just surfaces, and the name of the file and the location the data are saved. In addition, the “optimise” page gives the user further options for the importation of the file into Jack. Most important of these for IGES file importation is the “spatialise” option, as the layers in IGES files are not preserved during importation (the Jack figure is composed of one large segment). The “spatialise” option divides the object into a number of segments (the user specifies the minimum and maximum triangles for each segment), for example, grouping a cockpit instrument panel into one segment. This is very important when dealing with large, complex objects, such as an aircraft cockpit or truck cabin. Allowing, for example, the cockpit doors to be made invisible to make positioning the human in the seat easier. Overseas experienced users of Jack report that the Stereolithography and VRML file formats result in the most stable imports⁵. Of the file formats assessed, the main advantage of the VRML format is that the layers are preserved (as segments) during importation making manipulation of the model in Jack significantly easier. Experience with importing models of cockpits into Jack has demonstrated that importing large CAD models can be a “hit and miss” affair with no clear reason for the success or failure of an importation. The solution to this problem is to break the model down into smaller elements and import these individually.

Table 1: A list of the file formats supported by Jack

Supported File Formats
Vis
VRML
IGES 5.3
Stereolithography
Inventor 2.1
Optimizer 1.1
Performer 2.1 binary
Deneb IGRIP 1.2 parts
Cyberware
BYU
Visualization Toolkit
Marching Cubes

⁵ Source: Richard Kozycki, US Army

4. Human Models

Once the virtual workspace has either been developed using Jack's tool set or imported from an external source the scene must be populated with anthropometrically realistic humans. This section describes the options available for creating humans.

Jack was initially developed for the analysis of human machine interfaces [20]. To support this, Jack humans have a lifelike, smooth-skin appearance, using realistic shaped geometries to represent the body parts. While the Jack model has a realistic appearance it is also computationally efficient, so the model can be manipulated in real time. The Jack mannequin has a complex kinematic linkage system that closely resembles the human skeletal structure and joints that obey physiological range of motion restrictions. The default Jack human figure model is composed of 71 individual segments, which are made up of 5182 polygons. The segments are joined together by 69 joints that have 135 degrees of freedom (for example, a hinge joint has one degree of freedom). A skeleton model of Jack is shown in Figure 14, which displays all the joints. The range of motion for each joint is based on data from three different sources: NASA [21], Louis [22] and Chaffin & Andersson [23], with some data not available from these sources "guestimated" [24]. Furthermore, the data for each degree of freedom of a joint can be changed if other data is available. In addition to modelling simple joints like the elbow and knee, Jack also has complex models of the shoulder and spinal column [25]. The shoulder complex is composed of two joints, a shoulder joint and a sterno-clavicular joint. The below the neck spine complex consists of 17 thoracic and 5 lumbar vertebrae for a total of 17 segments and 18 joints. Each of the spinal joints has three degrees of freedom of movement and the joints move in an interdependent fashion using an inverse kinematic algorithm.

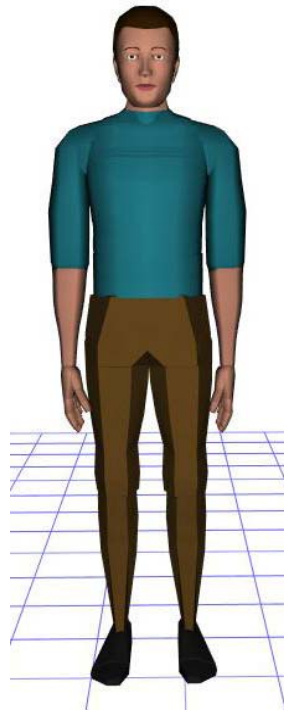


Figure 13: A 50th percentile stature Jack male mannequin

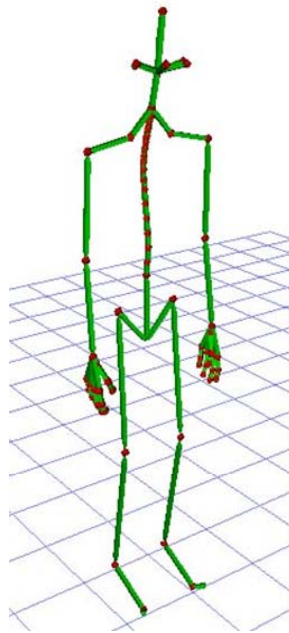


Figure 14: The Jack mannequin is composed of 71 segments, and 69 joints that have 135 degrees of freedom

4.1 US Army 1988 Anthropometry Database

The main Jack anthropometric database is based on the last comprehensive survey of the US Army [26]. This survey measured nearly 9000 male and female military personnel, following the awareness of the deficiencies of previous surveys. The survey was conducted at 11 US Army posts during a 12 month period in 1987 and 1988. A diverse range of 132 measurements were taken manually, along with 26 three-dimensional co-ordinates of the head and face. Measurements recorded included overhead finger tip reach, sitting wrist height, buttock-knee length, seated height and knee circumference. A summary of some of the key anthropometric measurements is shown for males and females in Table 2 and Table 3, respectively.

Table 2: A summary of some of the key measurements for males from the 1988 US Army survey

Measurement	Mean	Standard Deviation
Stature	175.8 cm	6.7 cm
Weight	78.5 kg	11.1 kg
Seated height	91.4 cm	3.6 cm
Buttock-knee length	61.9 cm	2.7 cm
Span	182.8 cm	7.7 cm

Table 3: A summary of some of the key measurements for females from the 1988 US Army survey

Measurement	Mean	Standard Deviation
Stature	162.9 cm	6.4 cm
Weight	62.0 kg	8.4 kg
Seated height	85.2 cm	3.5 cm
Buttock-knee length	58.9 cm	3.0 cm
Span	167.2 cm	8.1 cm

4.2 Mannequin Creation

4.2.1 Basic Mannequin Scaling

Jack comes with a number of options for the creation of realistic mannequins. The basic human scaling panel allows the user to create male and female mannequins with 1st, 5th, 50th, 95th and 99th percentile stature based on the 1988 US Army survey [26]. The mannequin's segments are then scaled using regression equations to create realistically dimensioned segment lengths. While these mannequins may be of value in the analysis of some workspace designs, the range of mannequin sizes available does not necessarily reflect the “hard to fit” members of a population. For example, a pilot of approximately average height, but who has long legs and a short torso may find it difficult to adjust the seat and rudder pedals to achieve the required over the nose vision, reach to controls and clearance with the cockpit structures.

4.2.2 SAE Mannequins

Society of Automotive Engineers (SAE) mannequins can also be imported into the Jack environment. Three mannequins, shown in Figure 15, are available: tall (187.2 cm tall), medium (171.4 cm tall) and small (155.1 cm tall).

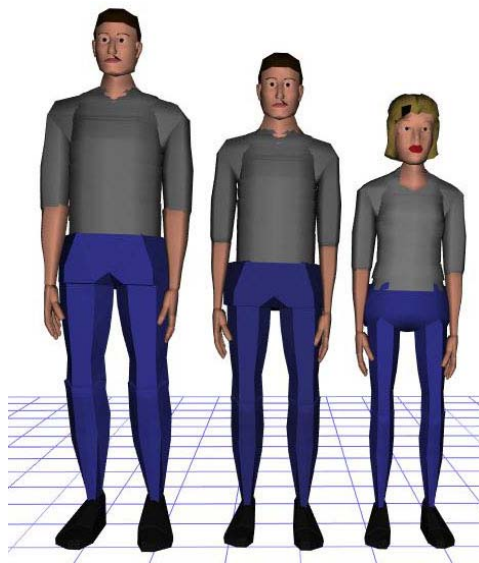


Figure 15: The large, medium, and small SAE mannequins

4.2.3 Advanced Mannequin Scaling

If anthropometric data is available for an individual, the anthropometric advanced scaling option can be used to create a Jack model of the person. The scaling panel allows up to 26 anthropometric dimensions (shown in Table 4) to be specified. Any measurements not supplied are calculated using regression equations based on the US Army data. Dimensions such as head and foot breadth are calculated based on the stature of the subject, while dimensions such as abdominal breadth are calculated based on stature and weight [27]. It should be pointed out, though, that not all the anthropometric dimensions are independent.

For example, interpupillary distance cannot be changed without changing head breadth. Each of the anthropometric measurements described in Table 4 are defined in the online help files for the Advanced Scaling Panel, they are not defined in the Jack manual. The definition of these measurements may be from one Jack site (a specific location on a segment) to another. For example, sitting height is measured from the site “lower_torso.proximal” to the site “bottom_head.top”. For other measurements, such as buttock-knee length, for example, the measurement is from the most rearward point on the gluteus to the most anterior point on the knee.

Table 4: *The anthropometric variables in the advanced scaling panel*

Number	Dimension
1	Stature
2	Abdominal Depth
3	Ankle Height
4	Acromion Height
5	Arm Length
6	Biacromial Breadth
7	Bideltoid Breadth
8	Buttock-Knee Length
9	Elbow Rest Height
10	Elbow-Fingertip Length
11	Foot Breadth
12	Foot Length
13	Hand Breadth
14	Hand Length
15	Head Breadth
16	Head Height
17	Head Length
18	Hip Breadth
19	Interpupil Distance
20	Shoulder-Elbow Length
21	Sitting-Acromial Height
22	Sitting Eye Height
23	Seated Height
24	Sitting Knee Height
25	Thigh Clearance
26	Thumbtip Reach

4.2.4 Principal Component Analysis – Boundary Mannequins

When designing an aircraft cockpit it has typically been a requirement that between 90 and 95 percent of the relevant population are accommodated. When specifying the proportion of the population to be accommodated a percentile method has been traditionally used. For example, if 90% of males were to be accommodated in a cockpit, it was assumed that by requiring the 5th to 95th percentile measurements for key cockpit dimensions (such as buttock-knee length and seated eye height) to be accommodated, then approximately 90% of the population would be accommodated. Unfortunately, due to the multivariate nature of human anthropometric dimensions, a much smaller percentage of people are accommodated. Furthermore, the larger the number of anthropometric requirements the greater the population restriction [28]. To illustrate the problem two examples are presented. In a study using US Naval aviator anthropometric survey data, the number of aviators who were within

the 5th and 95th percentile limits for 13 cockpit relevant anthropometric dimensions was calculated. After passing the subjects through all 13 criteria, 52.6% of the subjects were eliminated, when it has been traditionally assumed that only 10% would be eliminated [29]. In another study that demonstrated the limitations of the percentile method, Robinette and McConville [28] broke the stature of female subjects down into seven linear segments. They then added the 5th and 95th percentile female values for each of these segments together and compared them to the 5th and 95th percentile statures. The sum of the seven 5th percentile segments was 136.89 cm, while the 5th percentile stature was 152.50 cm, a difference of 15.61 cm. For the 95th percentile case, the sum of the seven segments was 188.81 cm, while the 95th percentile stature was 173.06, a difference of 15.75 cm.

Following the identification of the problems inherent in the percentile method, a statistical technique was developed called principal component analysis (PCA). PCA is a data reduction technique that minimises the number of dimensions needed to describe anthropometric variability by combining related measurements into a set of factors based on their correlation [16]. Using the PCA technique, Jack can determine the boundary mannequins that represent the anthropometric extremes of the specified percentage of the male, female, or male and female populations. Figure 16 shows eight boundary Jack mannequins representing the central 99% of the US Army male population. Note the difference in the relative limb lengths of some of the mannequins. For example, the mannequin fourth from the left in Figure 16 has arms considerably shorter than the mannequin fifth from the left. Clearly, these two mannequins will have different cockpit accommodation issues, the mannequin on the right easily reaching controls out of reach to the mannequin on the left.

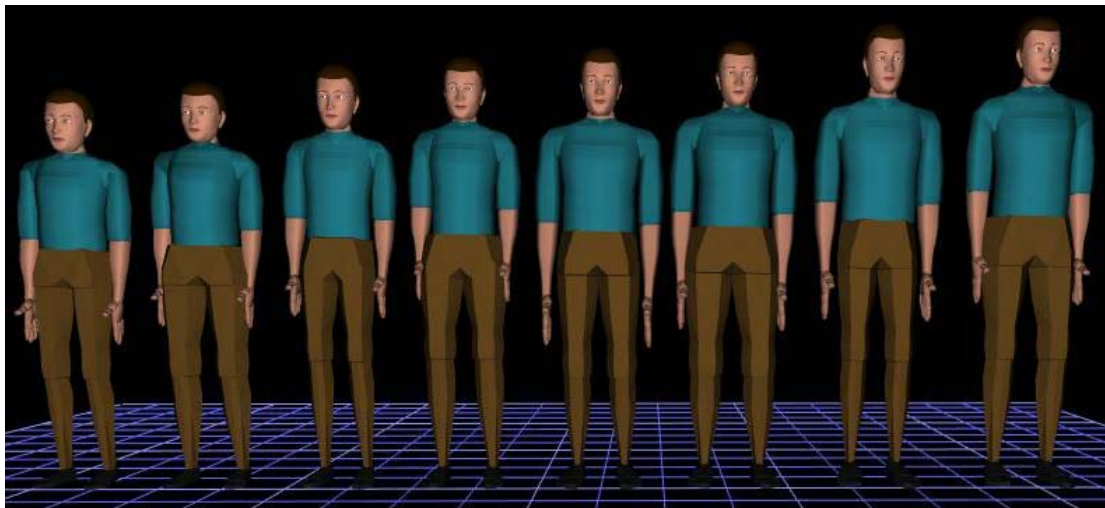


Figure 16: Eight boundary mannequins that enclose 99% of the US Army male population

4.3 Clothing and Equipment

Clothing and protective equipment play an important role in many work environments, especially military environments, including cockpits [30]. In the military aviation environment many risks potentially face the aircrew, including those due to acceleration, noise, temperature, and ballistic and biological attack. Depending on the number and severity of the

potential risks, the clothing and equipment worn by military personnel can become quite bulky and can affect the range of movement, posture and position of the aircrew. Ideally, the bulk and encumbrances caused by the clothing and equipment should be taken into account when performing an assessment of the human machine interface. Jack allows a mannequin to be clothed and equipped, although no library of clothing is available and limited equipment is available (for example, ladders, spanners, and hard hats). A review of the literature reveals only limited attempts have been made to model clothing and equipment and its effect on subject position, posture and range of movement. One study that looked at several options for modelling clothing and equipment in the Jack environment is described below.

Kozycki [31] assessed several methods for modelling the encumbrance and restriction of clothing and equipment that were suitable for the real-time analysis of a cockpit design. One option assessed involved attaching a texture map of a two-dimensional image of clothing onto the three-dimensional human model. For example, mapping a camouflage pattern onto the Jack figure. While this would enhance the visual realism of the model, it would not model the effect of clothing bulk on the mannequin's range of motion, for example. Another method explored involved expanding the figure's segments to approximate the bulk and thickness of the clothing, however the uniform expansion of the segments was found to lead to an unrealistic mannequin with parts of the segments that were out of proportion. The method chosen involved digitising the individual items of clothing and equipment (in this case the clothing and equipment worn by an attack helicopter pilot), creating models of each item of between 3000 and 5000 polygons. Items digitised for this study included a pistol, shoulder holster, over water suit and a thigh mounted clipboard. The clothing and equipment items were then placed on the mannequin (Figure 17). To incorporate the effect of soft tissue and clothing compression, duplicate clothing segments with appropriately reduced dimensions were added to the mannequin. To determine the available range of motion of each joint a collision detection algorithm was used between these reduced dimension segments. A small validation trial was conducted that demonstrated the feasibility of this approach, which was then used in the Comanche helicopter redesign project [15].



Figure 17: A mannequin in the Apache helicopter with a range of clothing and equipment (used with permission)

4.4 Mannequin Posture

By default when a new mannequin is created in Jack it is standing in an erect posture. To transition Jack to another posture by adjusting all the required joints is potentially very time consuming given Jack has 69 joints. To make the process more efficient, Jack has a library of postures such as standing straight, standing relaxed, seated relaxed, kneeling on one knee, driving and crawling. Examples of some of the postures available are shown in Figure 18. It is also possible to add user developed postures to the library. So, for example, if data has been gathered on a pilot's posture via photography or the digitisation of key anthropometric landmarks on a test subject, this data can be used to create a posture in Jack, which can be saved for later use. In addition, Jack also has a hand shape library (Figure 19), which includes hand shapes such as fist, precision grip and point.

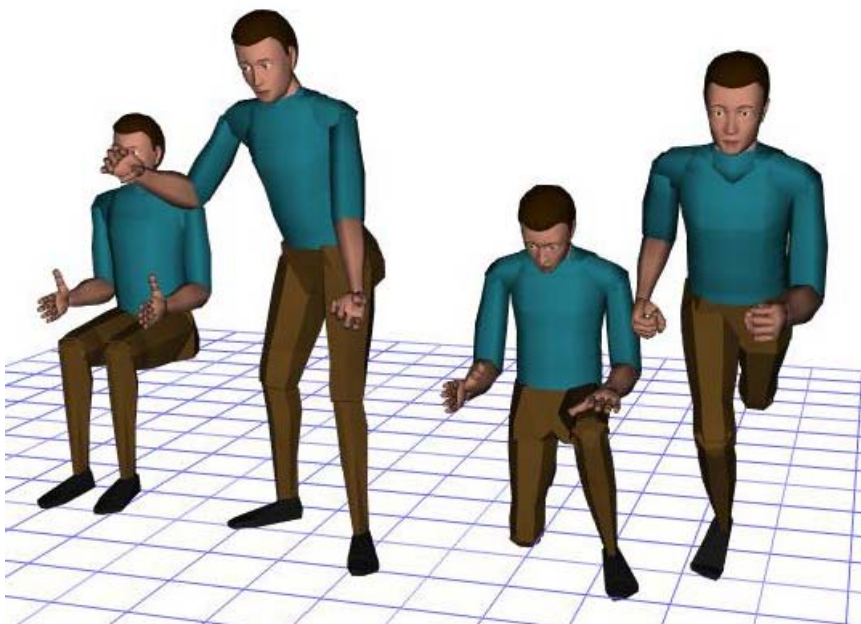


Figure 18: Jack has a library of 28 postures and additional postures can be easily added

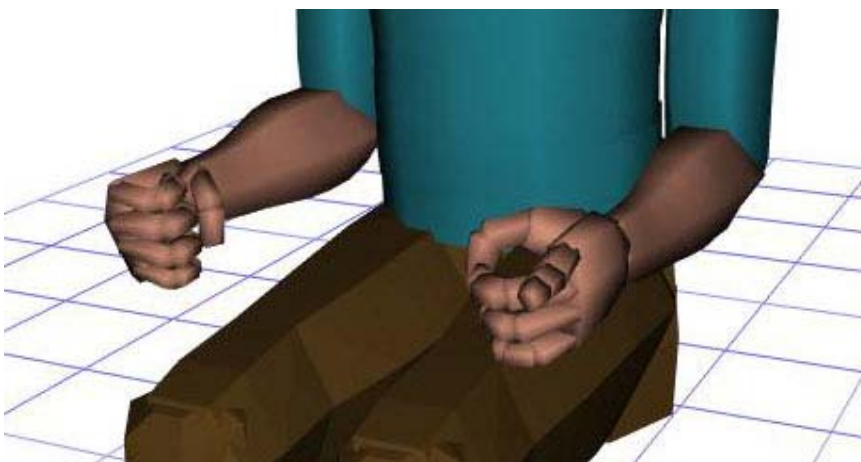


Figure 19: Two examples of hand shapes available in the library, right hand fist and left hand point

4.5 Mannequin Control

Because of the complexity of the joint linkages in the Jack model, it can be very laborious to determine if, for example, a mannequin's hand could reach a switch in a cockpit by adjusting each of the joints involved individually. One easier option is to use the posture library as described above, to approximate the required final posture, and then adjust the joints involved to achieve a realistic final posture. Another option is to use the human control panel, shown in Figure 20, which uses Jack's in-built inverse kinematic algorithms to determine how Jack will move based on the behavioural constraints selected. The human on the left hand side of Figure 20 allows the user to select the behavioural constraints that will act on the mannequin. Options for the limbs include holding the hand or foot relative to the human, an object, the world or a specified site, or the limb can be required to mirror the movement of the opposite limb. In addition, for the arms, the user can specify whether the reach takes place from the shoulder or from the waist, which would allow the simulation of reach by a pilot with locked or unlocked inertia reels. The torso can be constrained to hold its current orientation or to remain vertical. The head and eyes can be required to fixate on an object, the eyes and head tracking the object as it moves. Once the behaviours have been selected, the human on the right can then be used to select the end effector that will be moved. The end effector (hand, for example) can then be moved to the desired point in space and the joints involved will be automatically adjusted using the inverse kinematic algorithms.

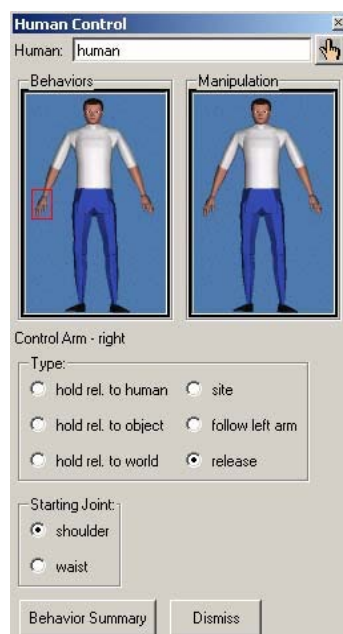


Figure 20: The human control panel – selecting behaviour options for the right hand of the human

5. Analysis Tools

When assessing the design of a workspace, such as a cockpit, a number of different issues must be considered. The analyst must ensure that the specified population can reach all the controls, maintain the appropriate internal and external field of view (for example, ensuring a pilot can see the instrument panel unimpeded and at the same time have the appropriate over-the-nose field of view), and perform the specified tasks unimpeded. Jack provides the user with a range of tools to conduct an ergonomic assessment of the virtual workspace.

5.1 Collision Detection

When evaluating a workspace it is important to ensure the human can complete all the required tasks while maintaining appropriate clearance with the workplace structures. For example, when ejecting from a fast jet, the pilot must have an appropriate clearance with the cockpit structures to avoid serious injury or death. Jack has four different collision detection algorithms that can be selected based on the requirement for the speed and accuracy of the collision detection calculations. Algorithms available include Gilbert and Johnson, bounding box, and bounding sphere. Following the selection of an algorithm, a collision list can be created which lists the pairs of segments (the segments can be either within an object or between objects) or figures for which the collision detection calculations will be made, along with the distance threshold for each pair. Once constructed, the collision list can then be checked continuously or on demand.

5.2 Reach Envelope

An important factor in determining accommodation in vehicles such as an aircraft cockpit or a car is the requirement to be able to reach all the hand and foot controls. Jack has a number of options for assessing reach using the reach zone tool, shown in Figure 21. The user can create a reach envelope for the hand with the motion restricted to the arm, as if a pilot was constrained by a harness (see Figure 22), or an envelope can be generated including axial rotation of the waist and a lateral and forward flexion of the trunk, simulating an unrestrained reach by a pilot. In addition, envelopes can be generated for end effectors other than the hand using the constraint driven option. For example, a foot reach envelope can be created by specifying the required end effector and the starting joint (hip, for example). Although there are many options available in the reach zone panel the documentation provided in the Jack manual is limited.



Figure 21: Reach zone options

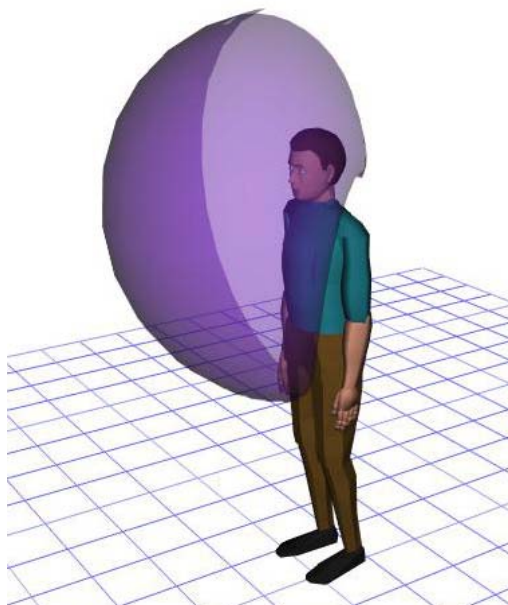


Figure 22: Jack mannequin with a reach envelope for the right hand

5.3 Distance Measurement

Jack has two measuring tools. The “measure distance” utility allows the user to determine the distance between two points (a finger tip and a cockpit control, for example) in a Jack scene. In addition, “rulers” can also be created between two points in the environment, which display the distance between the two points. The “rulers” are dynamic, so as the points move the displayed distance changes.

5.4 Vision

5.4.1 Eye View

Jack provides an approximation of what the mannequin can see out of either eye or both eyes combined. The view does not represent the complete field of view available to a human (typically extending to about 200° in the horizontal), only the central portion of the field of view.

5.4.2 View Cones

View cones, shown in Figure 23, can also be displayed for a human, with the user able to specify the angular extent of the view cone and its length. This feature is useful for cockpit assessments, ensuring displays are within the appropriate viewing angle for the specified population.

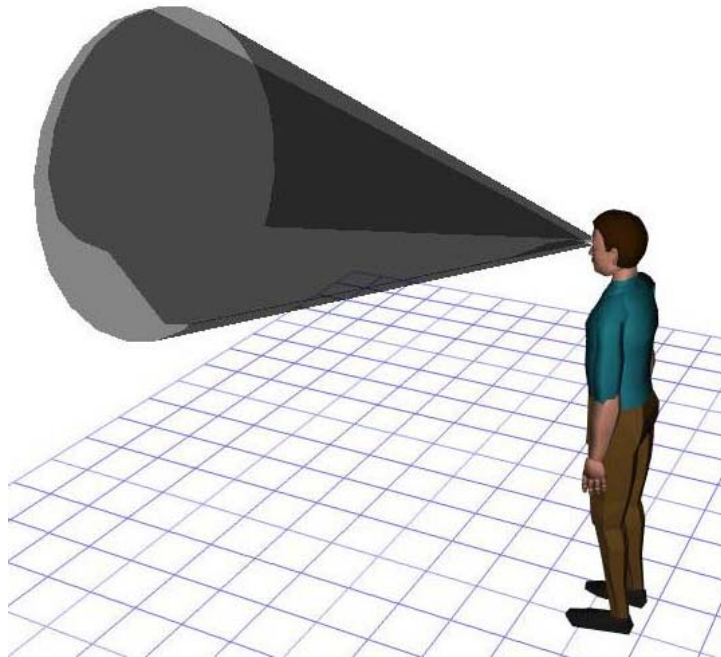


Figure 23: Human with view cones

5.4.3 Mirror Modelling

Many vehicles, such as cars, trams and some helicopters have mirrors to maximise the driver's field of view around the vehicle. Mirrors can be modelled in Jack by changing the property of a face of an object to reflective. An example of a mirrored face is shown in Figure 24.

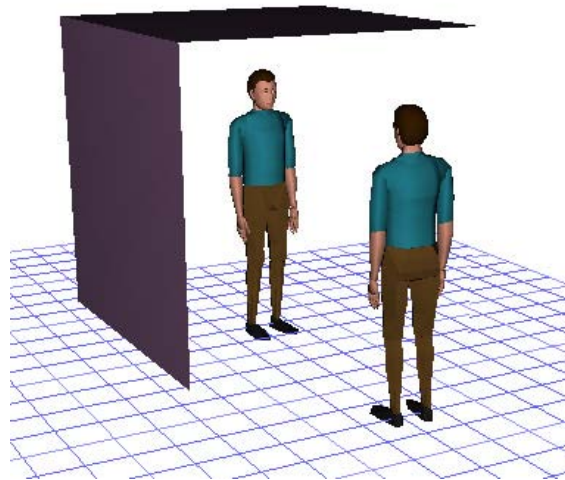


Figure 24: Mirror image of Jack mannequin - reflection option set for the cube face

5.4.4 Joint Forces and Torques

Jack can calculate the forces and torques acting about any joint in the mannequin. In addition, weights can be attached to sites on the mannequin simulating the effect of a piece of equipment on the body, for example. A graphical summary of the forces and torques can be provided for the selected joint or body branch (arm or leg, for example).

6. Exportation

One of the key advantages of software such as Jack is the ability to export the results of an analysis and present them to the clients in a graphical fashion, clearly demonstrating any ergonomic problems and solutions. The Jack exportation options are discussed below.

6.1 CAD Model Exportation

Jack allows individual figures or the whole environment to be exported in either the IGES 5.3 or VRML 1.0 formats. In a test of the exportation function, a four megabyte IGES file was imported into Jack, then exported in IGES 5.3 format. The resulting IGES file was 160 megabytes, making this option impractical. In contrast, the same figure exported in VRML 1.0 format resulted in an eight megabyte file.

6.2 Screen Capture

Jack provides a screen capture tool that allows the user to take a snapshot of the selected graphics window. Four different formats are available: jpeg, tiff, bitmap and portable pixel map. In addition, the image can be rendered (up to 23 passes) to minimise any jagged edges.

6.3 Animation

Jack has the ability to create an animation of a task simulation. Although, it should be noted that the creation of an animation can be very laborious, as it must be created frame by frame.

7. Computer Requirements and Installation

The Jack software can run in a number of environments, including Windows XP and 2000, along with HP-UX and IRIX. Ideally, installation of any software should be a straight forward process. Unfortunately, this is not the case with Jack version 5.1. Two problems have been identified which unnecessarily complicate the installation process⁶. Firstly, the directory name for the Jack files must not contain spaces (most likely a legacy of Jack's initial development in the Unix environment). Secondly, the Flexlm license manager must be correctly configured.

8. Training and User Support

8.1 Training Materials

A comprehensive training manual is provided on the Jack version 5.1 installation CD. In addition, online help is available via the help pull down menu on the control toolbar. The information presented in the paper Jack manual and the online help files are not the same, so both sources need to be consulted if one source does not provide an adequate explanation. For example, the Jack manual provides only a limited explanation of the options available when importing a CAD model into the Jack environment. In contrast, the online help contains a link to a portable document format file that provides a detailed explanation of the options available when importing files.

8.2 User Support

Requests for assistance with Jack have typically been sent directly to the Jack developers. Generally, any queries have been answered in a timely fashion and responses have provided adequate detail. In addition, patches have been provided promptly for any reported bugs.

9. Model Limitations

While human modelling tools like Jack offer huge advantages to the human factors practitioner, enabling the cost effective and timely evaluation of workspaces, they also have a number of limitations that must be considered before using the model. Two of the main limitations of Jack are highlighted here. The standard Jack human, shown in Figure 13, is

⁶ Problems identified by D. Stratton, University of Ballarat

described by at most 26 anthropometric dimensions, which are listed in Table 1. This mannequin could be suitable for tasks like the ergonomic assessment of a cockpit, for example, ensuring the specified population can reach all the controls and have the appropriate field of view. However, a mannequin with this level of detail would not be suitable for the assessment of personal equipment fit for a pilot. For example, the Jack model of the head is described by only three anthropometric dimensions (length, breadth and height), which does not specify the shape of the head sufficiently to assess helmet fit. For tasks like the assessment of equipment fit, where an exact fit is vital, higher fidelity models of an individual's body shape are required. Software has been developed by the US Air Force Computerised Anthropometry Research and Design Laboratory specifically for the assessment of the fit of personal equipment and clothing using laser scans of the human and equipment [32]. Also, when evaluating a seated work environment, such as a cockpit, care must be taken to accurately model both the posture and position of the seated subject. This can be achieved by digitising the relevant anatomical landmarks on a test subject in the workspace and using these landmarks to position the mannequin. In addition, photographs can be used to assist with positioning.

10. Validation

Human modelling tools have been applied to a diverse range of problems in the aviation, automotive, defence and manufacturing industries since the late 1960s, from the determination of the grip height on a weed trimmer to the design of the International Space Station [3]. Although tools like Jack have been applied across a broad spectrum of problems, only a limited number of reports on the validation of Jack have been published in the open literature. Two Jack validation activities relevant to seated workstations that have been reported in the open literature are described below.

A collaborative project involving the Netherlands Organisation for Applied Scientific Research (TNO) and the United State Air Force assessed the validity of five of the major human modelling tools (including Jack, RAMSIS and Safework) for cockpit accommodation analysis. The first phase of this work focussed on an assessment of the anthropometric accuracy of each of the five mannequins, and the results were presented at the 2000 Digital Human Modeling conference [33] (only a powerpoint presentation was included on the conference proceedings CD). Limited information is provided in the presentation on the methodology employed in this study, but some of the key results of the study were reported. Forty anthropometric measurements were taken of eight volunteers and these measurements were used to create mannequins using the five human models. A comparison of the absolute error percentages of 13 anthropometric measurements for Jack version 2.2 ranged from 0.5% for stature to 8.4% for crotch height and buttock-knee length. Of the five mannequins, the Safework mannequin was the most accurate, with the greatest error being for elbow height sitting (2.5%). Improvements in the Jack mannequin scaling in version 2.3 resulted in the error percentage being reduced to zero for all 13 measurements (most likely sample dependant). The plan for the next phase of the project was to produce cockpit accommodation guidelines for a F-16D fast jet using each of the five models [34]. The results from the five models would then be compared to guidelines produced using the live subject technique employed by the

United States Air Force [35]. Hudson and Zehner reported that they planned to pay particular attention to modelling the posture and position of the mannequin in the cockpit, and the effect of the restraints on the mannequins's reach. A TNO report was published on the results of this assessment but the report is commercial-in-confidence⁷.

Kozycki [31] conducted a small validation study of Jack version 1.1 as part of an assessment of the suitability of Jack to model the encumbrance and bulk of four different clothing and equipment ensembles typically worn by US Army attack helicopter pilots. Two helicopter pilots dressed in flight gear were secured in an Apache seat by a five-point harness. Using a video-based motion-capture system, the range of motion of the right and left hands of the subject was recorded in several horizontal planes. A model of the seat was then imported into Jack, and mannequins were created from measurements taken of the two pilots. These mannequins were then clothed and equipped in equivalent ensembles to those worn by the subjects. Key anatomical landmarks were digitised on the pilots and these were used to position the mannequins in the seat. A comparison of the data recorded for each horizontal plane showed the mean difference between the reach of the pilot and the mannequin to be approximately 1 to 2 cm. Even though the pilots were firmly restrained by a five-point harness, and they were instructed not to move their torso, some torso movement was observed, which most likely explains most of the difference in the reaches. The results of this small trial demonstrated the feasibility of this approach, which was then used for the Comanche helicopter redesign [15].

11. Concluding Remarks

Jack is widely used in the automotive, aviation, manufacturing and defence industries by organisations like Ford, United Defence, NASA and the US Army. The model has played a key role in numerous projects, including the development of the International Space Station and the redesign of the Comanche helicopter. Over the last twenty years, the Jack human model has evolved from a simple, unrealistic arrangement of polygons, to a highly realistic representation of a human. The model's joint linkage system closely resembles the human skeletal structure, the joint ranges of motion are physiologically based and the geometric shell closely resembles the shape of a human. Furthermore, humans can be created based on recent comprehensive anthropometric surveys, as well as by specifying up to 26 individual dimensions of a person. A range of behavioural controls can be specified, allowing the movement of the human to be constrained based on the selected behaviour. Virtual workspaces can be constructed using Jack's native CAD modelling tools, or CAD models can be imported using third-party translators. Furthermore, a range of ergonomic analysis tools are available to assess the design of workplace, including tools to assess reach and field of view.

⁷ Source: Aernout Oudenhuijzen, TNO.

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19. ABSTRACT When evaluating the design of a workstation human factors practitioners have traditionally used a number of different approaches to assess the design, including two-dimensional drafting mannequins and physical mock ups. In the late 1960s, human modelling software became available, and aerospace and automotive manufacturers saw the potential for much of the design process to take place in a virtual environment. Modern human modelling tools include Jack and Ramsis. As part of Project MIS 872, the Defence Science and Technology Organisation was supplied with a copy of Jack. This report serves as a review of the base Jack tool (version 5.1), with specific focus on the features relevant to the assessment of seated workstations.					