

Technical note

A CAD analysis programme for prosthetics and orthotics

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Abstract

A CAD (computer aided design) analysis software package (CADVIEW) was designed for use with prosthetic and orthotic CAD CAM (computer aided design/computer aided manufacture) systems. Using the Microsoft Windows 3.1 environment, CADVIEW provides a series of anatomical shape viewing and analysis tools. These tools include simultaneous display of multiple sockets and multiple views, two dimensional (2D) and three dimensional (3D) measurement, shape statistics, multi-shape alignment, cross-sectional comparison, colour coded 3D comparison, resolution enhancement, and image copying capabilities. This programme should be of benefit to clinicians and researchers who wish to assess and/or compare CAD data generated by MS-DOS based CAD CAM systems.

Introduction

As prosthetic and orthotic CAD CAM systems become integrated into clinics and workshops, the assessment and analysis capabilities available with this digital storage format can create new opportunities for patient evaluation. The potential of CAD CAM as an educational and analytical tool has previously been documented in a variety of sources (Bednarczyk *et al.*, 1992; Fernie *et al.*, 1984; Sidles *et al.*, 1989).

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To analyse changes in limb volume, a manual digitiser/computer analysis system was developed by Bednarczyk *et al.* (1992). Analysis software was written to determine the effects of clinical interventions on limb oedema. By digitising an anatomical shape into a computer and using the resulting three-dimensional (3D) coordinates to estimate limb volume at various stages during treatment, a quantitative measure of volume changes with time was obtained. Although this system was sufficient for measuring volumes, it lacked the graphical and analytical tools necessary to examine prosthetic and orthotic devices.

Fernie *et al.* (1984) used a laser scanning CAD system to examine student prosthetist fitting methods. Plaster positive models from sixteen students (96 fittings) were digitised before and after modification and input into a graphical display package. The teacher and student could examine sagittal and coronal profile views and three transverse cross-section images. Initially the clinicians had difficulty interpreting the two-dimensional (2D) output; however, interpretation improved as these people became familiar with the system. This quantitative method was considered beneficial since more information was available to assess student fittings over the brief trial period. While this approach was better than the technique of Bednarczyk *et al.* (1992), the necessity of using a laser scanner and the lack of 3D graphical display and analysis limited the global application of this system.

Sidles *et al.* (1989) outlined a software tool

that used 3D graphics to compare the results of two socket designs. Their software package compared two digitised socket shapes based on the distances between the surfaces and graphically displayed a composite view of the differences (for example a CAD CAM socket and a manually made socket). The composite view involved displaying one socket on the screen with the differences at each point on the surface represented by a corresponding colour or shade. This technique was effective for education (comparing a student's sockets to an "ideal fitting"), clinical studies, research, and in improving fabrication design tools.

Although previous systems have addressed specific educational and analytical needs, a comprehensive analysis package would provide the tools necessary to examine patient shape characteristics from CAD generated data. This document describes a computer programme (CADVIEW) which offers a series of analysis tools for MS-DOS based, prosthetic and orthotic CAD CAM systems. This software provides features that are presently unavailable in current, MS-DOS based, prosthetic CAD CAM programmes including: display of multiple sockets and multiple views, 3D measurement, shape statistics, multi-shape alignment, cross-sectional comparison, colour coded 3D comparison, and resolution enhancement.

Methods

The CADVIEW software package was developed to offer a consistent and user friendly environment for viewing, comparing, and analysing CAD generated anatomical shapes. To fulfil these objectives, the Microsoft Windows 3.1 environment was selected as the appropriate software platform since it was:

- a common system for MS-DOS based computers
- a standardised, user friendly, graphical interface
- compatible with most computer hardware (i.e., graphic cards, printers, etc)
- able to run multiple programmes concurrently
- able to transfer data and images between programmes.

While CADVIEW can work with data from any prosthetic CAD CAM system, current input options include CANFIT-PLUS and IPOS Systems II CAD data files. The user may load

either raw digitised data, measurement generated data, or CAD modified data. Anatomical landmarks are loaded and displayed as part of the raw digitised or CAD modified data file. The following sections will describe the viewing, analysis, and comparison tools included with this software.

Image presentation

Multiple document interface

CADVIEW implements a multiple document interface approach for image presentation. This environment allows the user to open a series of socket data files or socket views from within the main CADVIEW window. The ability to display and simultaneously view multiple images is only limited by available memory and screen space. A multiple document interface is beneficial for viewing a series of sockets from the same client, teacher versus student sockets, or different fitting approaches. Multiple 2D images can also be displayed, thereby permitting visual comparison of cross-sections or profiles at different positions on the 3D shape.

Three dimensional view

A satisfactory 3D representation of the socket/orthosis shape is very important for viewing and comparing CAD data files. By combining the graphics capabilities of Microsoft Windows, facet shading techniques, and a resolution enhancement function, a lifelike on-screen image can be displayed. In addition to the shaded view, the 3D image can be displayed as a wireframe or composite (shaded imaged with superimposed wireframe). The wireframe view is the fastest to redraw on screen and provides useful reference marks when measurements are being taken from specific locations on the shape. A shaded view, while taking longer to redraw, provides the best representation of surface contour. Anatomical landmarks recorded during the digitising process may be displayed on the 3D shape to provide comparison reference points.

The 3D shape may be rotated in the frontal plane, sagittal plane, and about the image longitudinal axis, thereby displaying the shape in any 3D orientation. A cubic reference box is located in the rotate window to help with shape positioning. Since the three rotation angles are entered numerically, the user can ensure that

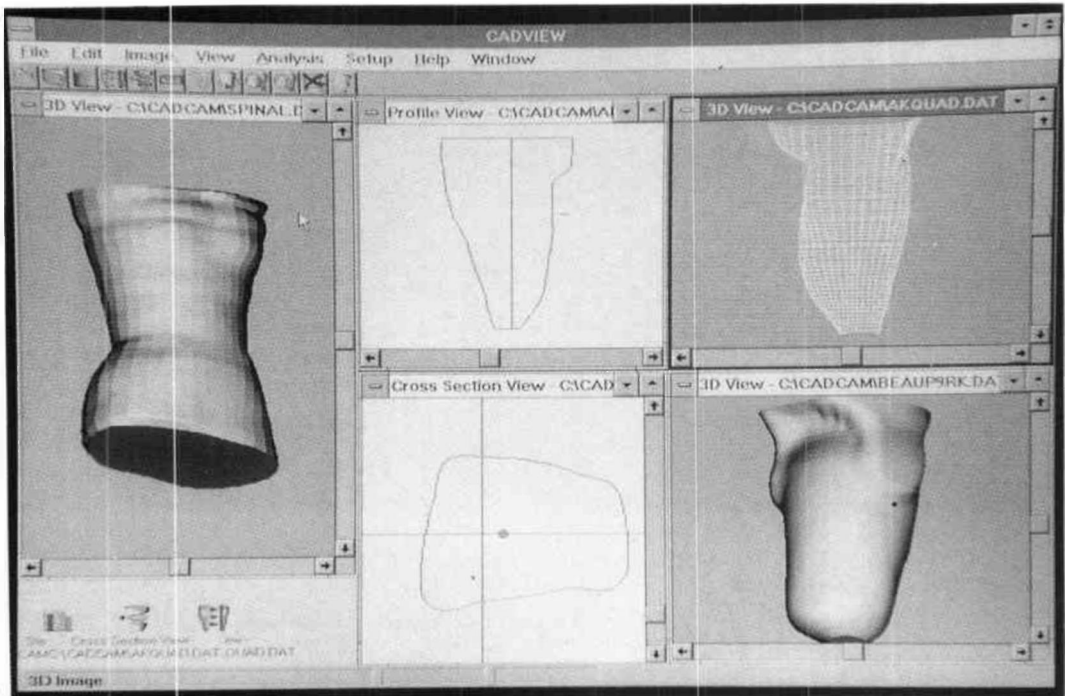


Fig 1. Multiple document interface.

multiple shapes are aligned correctly before comparison. As well as shape rotation, the image may be moved about the screen or enlarged to better assess individual regions.

Resolution enhancement

In cases where insufficient digitised data points are available to create a satisfactory on-screen image, a mathematical interpolation option is provided to increase image resolution. Initially, a linear interpolation was used to add points to the cross-section and profile views; however, this approach did not have any effect on improving the 3D image. Since the slope between data points remained constant the angle between new surfaces and the light source was unchanged, thereby causing all surrounding surfaces to be shaded the same colour. To deal with this problem, a cubic spline interpolation was used to calculate new cross-sections along the length of the shape and new data points on each cross-section. While increasing the image resolution increases redraw time, a three to five factor resolution enhancement can produce a near photographic quality image of the prosthetic/orthotic shape.

Two dimensional views

Multiple cross-section and profile views can be displayed on screen for each 3D image. Cross-section or transverse slice images are useful for viewing shape contour, taking medio-lateral or anteroposterior measurements, and changing the socket statistics display. Profile sections, or longitudinal slices, are useful for viewing the complete shape at different angular positions, making length measurements, and changing the symmetry statistics. To help compare 2D or 3D images, the cross-section and profile locations are simultaneously displayed on the 3D image as a thin line.

Image transfer

Using the standard *Copy* transfer procedure, a clinician may transfer 2D or 3D images between CADVIEW and most other Microsoft Windows programmes. This feature is useful for copying a 3D image to a drawing or painting programme, annotating the image with highlight boxes or text, and transferring the annotated image to a word processor for inclusion in internal or external correspondence (i.e. patient

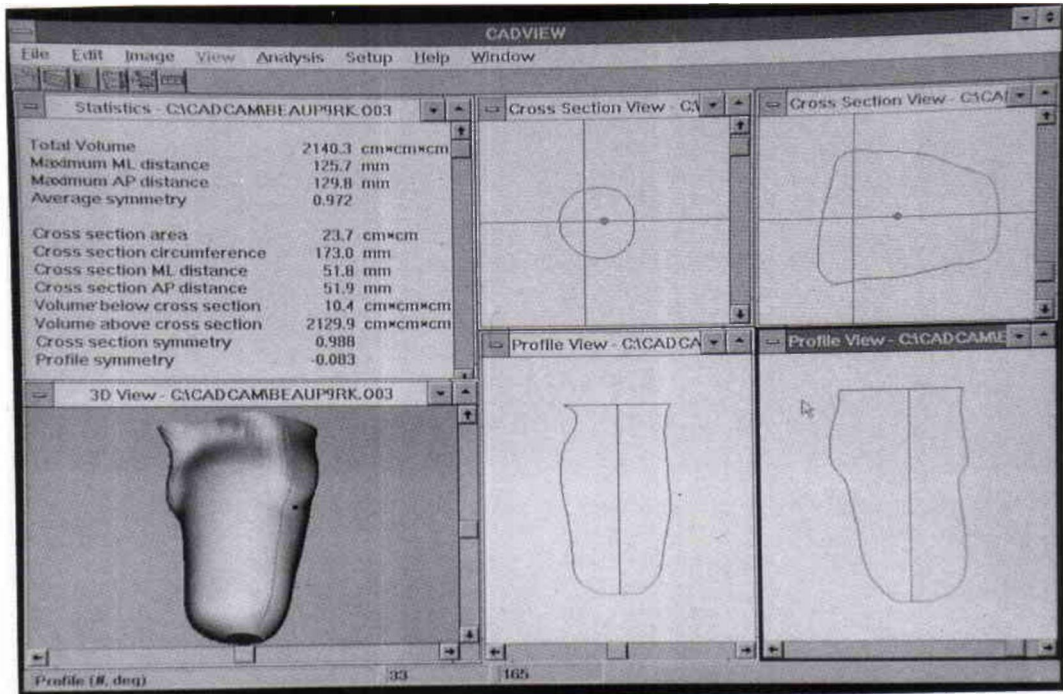


Fig 2. Two dimensional views.

file, insurance companies, etc.). The image transfer programming routine employed the Windows Metafile format for data exchange and followed standard Windows guidelines.

It should be noted that a 256 colour shaded image (SuperVGA) can only be successfully copied to programmes that can process the size of colour palette; therefore, 3D wireframe images are often recommended for data transfer. To deal with image transfer/printing limitations, a print feature was included in CADVIEW which sends the active window contents directly to the default printer. Test cases on a Hewlett Packard Laserjet III provided accurate reproductions of 256 colour shaded shapes. Since most printers provide Microsoft Windows drivers, CADVIEW can be used as an intermediary between existing CAD software and non-postscript printers.

Analysis

Quantitative assessments of individual prosthetic/orthotic shapes are accomplished by using the statistics and/or measurement features.

Statistics

The predefined measurements and statistics

can be divided into overall and cross-section components. Overall information includes total volume, maximum mediolateral (ML) distance, maximum anteroposterior (AP) distance, and average symmetry. Calculation of the total volume involved multiplying each individual cross-sectional area by half the longitudinal distance between the slice above and the slice below and summing these values over the entire shape.

Cross-section information includes area, circumference, ML distance, AP distance, volume above the cross-section, volume below the cross-section, and symmetry. A symmetry statistic was also included for the profile view. The cross-sectional data window is updated as different 2D images are displayed on screen, thereby simultaneously providing the user with cross-section or profile display, the position of the slice on the 3D image, and statistics related to the slice being displayed.

Cross-sectional areas were obtained by summing the triangular areas defined by adjacent radial length values. Symmetry statistics were calculated by dividing the cross-section or profile into two halves. The cross-section division point was at the main reference

mark and the profile division point was along the vertical, polar coordinate, axis. Corresponding radial lengths from the origin to the 2D surface coordinates were used to calculate a Pearson correlation coefficient between the two halves. The closer the correlation coefficient is to one, the better the symmetry between the two sides. It should be noted that this method only considers the surface shape and not differences in magnitude.

$$\text{Area} = \sum_{n=1}^{\text{\#sections}} \frac{(ab \sin(C))}{2}$$

where: a = length of first triangle side
 b = length of second triangle side
 C = angle between a and b

AP and ML distances are initially set at the main reference position (AP) and at 90 degrees to the AP line (ML). A user may graphically change the AP or ML measurement location to any point along the socket by positioning the cursor on the AP or ML division line (located in the cross-section window), pressing the mouse button, and dragging the line to the new location. The division line is maintained at the same relative position for all cross-sections.

Measurement

On-screen measurement capabilities allow the clinician to obtain the linear distance between any two visible points. This measurement is similar to taking a caliper reading off a plaster positive. By pressing the mouse button and dragging the cursor about the screen, the distance between the initial and current mouse position is continuously displayed in millimetres.

Measurements in 2D windows are accomplished by scaling the number of pixels between the initial and current mouse position. This allows the user to take measurements at locations that are not necessarily on the shape; such as, from the centre of a cross-section to the edge. To obtain valid measurements from the 3D shape, the 3D coordinate at the current mouse position is obtained from the image data file and used to calculate the inter-point distance. This provides accurate measurements at any image orientation,

Comparison

The comparison section provides a means to

compare two shapes graphically and statistically. Shape comparison is useful for examining modifications on the original anatomical shape and/or comparing client progression over time. Using a currently loaded data file as the base, a second data file is opened for comparison. If these two shapes are not aligned on the same axis (i.e. two different digitisations) the programme can attempt to align both shapes to a common axis using the following procedure:

- calculate the centroid of each cross-section
- determine the line of best fit through the centroids
- rotate all data points about the origin until the line is positioned along the vertical axis
- calculate new perpendicular cross-sections using a cubic spline interpolation

This procedure is repeated five times to obtain a satisfactory result. Inter-shape comparison can now be performed since the new 3D data points are at the same angle and the same cross-section height. A root mean square error statistic is calculated using the distance between corresponding 3D data points on the original shape and comparison shape.

To test this positioning method, a series of trans-tibial stump casts were digitised using the CANFIT-PLUS software (VORUM Research) and the Seattle Digitizer (MIND). These shapes were redigitised at a five to ten degree angle to the original alignment and loaded into CADVIEW for comparison. The root mean square error between the shapes was 1.7 mm ($\sigma=1.0$). Examination of the effect of this procedure on shape alignment showed that the origin, which is set at the longitudinal midpoint of the shape, is not necessarily the optimal pivot point for rotational positioning. By introducing a graphical method for repositioning the origin before manually rotating or translating the shape, inter-shape error was reduced to under one millimetre.

Graphical comparison features include a dual wireframe view, colour mapped view, and dual cross-section view. A dual wireframe view superimposes a wireframe image of the comparison shape on the original shape. This view is helpful for assessment of inter-shape alignment and for locating areas that are not common to both shapes. The colour mapped view shades the original shape based on the distance between 3D data points. A negative

distance (concave) is shown as a shade of red while a positive image (convex) is shown as a shade of blue. Maximum and minimum shade values can be defined by the user. The inclusion of a minimum shaded threshold is useful for locating areas of change since areas without substantial modifications will not be coloured. Dual cross-section views superimpose corresponding cross-section slices from the original and comparison shapes on screen. This view is helpful in visualising local changes between shapes.

User services

An on-line help facility and programme customising options have been included with CADVIEW to assist the user with programme function and to accommodate individual tastes. Using the standard Microsoft Windows help interface, the clinician can search for information on any feature available in CADVIEW without leaving the programme. The customising section allows the user to change background, line, and shading colours; adjust the picture plane for 3D imaging; and change the mouse sensitivity for measurements.

Conclusion

A prosthetics and orthotics CAD analysis programme was developed to provide a graphical and quantitative means for comparing and analysing anatomical shapes. The ability to view multiple shapes on screen, perform measurements, obtain total and sectional

statistics, and compare two related images allows the user to examine the effects of prosthetic and orthotic interventions in a qualitative and quantitative manner. In combination with the user interface, data sharing, and graphical features of Microsoft Windows, this programme is a beneficial tool for both clinicians and researchers.

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