Articulation of Customizable Biomechanical Designs through Assembly Modeling

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ABSTRACT

The modeling and assembly of devices that interface with the human body pose unique design problems due to the complexity of human surfaces, the absence of traditional mechanical design techniques that apply to biomechanical design, and the lack of parametric strategies for biomechanical products. This paper presents a design strategy that utilizes top-down assembly modeling techniques using human scan data as the base part in an assembly. This method allows for the identification of mating conditions of products, the product-human interfaces, and aids in defining geometric relationships between product geometry and the human body. This method also identifies parametric strategies that utilize these geometric relationships to allow for the exploration of mass customization for products that interface with the human body.

Keywords: Biomechanical design, mass customization, assembly modeling, parameterization

1. INTRODUCTION

Parametric modeling techniques for customizable products that interface with the human body present unique problems due to the complexity of the interfaces, the deficiencies of typical mechanical design tools, and the lack of appropriate parametric design strategies. This paper presents a new strategy for creating parametric models for products that interface with the human body by using assembly modeling techniques.

Many types of products interface, or come into contact, with the human body. Such devices are typically referred to as biomechanical devices and include helmets, protective equipment, prosthetics, and orthotics. These products take into account human modeling techniques which involve the representation of human characteristics either through geometric models, engineering analysis, or mathematical equations [22]. Human characteristics can be in the form of geometric measurements of anthropometric landmarks, or measurable features on the human body that are present on all people, such as the nose, eyes, shoulder, etc. In designing biomechanical devices, the designer must take into account the human aspects of interface criteria in addition to mechanical design criteria used in traditional design. Because of the uniqueness of each human body, mass customization and parametric modeling is an ideal strategy for biomechanical products. However, the complexity of the design and the design process for these types of products makes most attempts at mass customization strictly cosmetic. Currently, devices that interface with the human body are designed using craftsman era design methods or traditional mechanical design techniques.

In craftsman era design, each product is designed and manufactured individually due to specific needs of a single customer. This method is used for products that require one-of-a-kind interfaces such as prosthetics or orthotics. They allow products to be designed for an individual, however, as a result, these products are generally expensive with long design cycle times and are generally not reproducible.

Biomechanical devices that do not require these individualized interfaces typically rely on traditional mechanical design methods. These methods result in products that are less expensive and have a faster concept-to-consumer cycle time. However, because traditional mechanical design tools such as CAD, CAE, and CAM (CAx tools), as well as design approaches were developed for the design of exclusively mechanical products, they lack techniques and methodologies that address the human aspects required for bio-surface and interface design, such as sensory requirements and pain thresholds. It is the authors' opinion that the most significant deficiency involves the lack of geometric tools for capturing and modeling human shape and form and the subsequent creation of interface geometry that meets biomechanical design criteria. CAx tools and systems do not provide adequate tools and there are not adequate methodologies using the existing tools and techniques to facilitate biomechanical design. As a result, these products, although faster than craftsman era products, still require lengthy design periods due to the difficulty in modeling products that interface with the body.

In addition to design process deficiencies, another significant deficiency in biomechanical design involves the lack of adequate parametric strategies for biomechanical design. The issue here is the difficulty in defining parameters associated with human surfaces as inputs. It is not clear what the most appropriate forms of mathematically representing the human surfaces are, let alone reducing the mathematical forms to a sub-set of consistent parameters. Consequently, it is not clear how to automate the design process. A great deal of work has been done to render current design tools parametric so as to support automation and mass customization [9]. However, since these tools and methods do not directly support biomechanical design, attempts at mass customization of biomechanical products are fragile, ineffective, and, for the most part, non-existent.

To address these issues, this paper presents a strategy of using assembly modeling to represent biomechanical products and their interface to the human body. This results in a top-down design method for devices that have a product-human interface. Although this promises to help in the process of biomechanical design, it does not necessarily solve all problems associated with biomechanical design and does not attempt to address the forces or mechanics involved in biomechanical design. Instead, this paper focuses on tools and techniques for the modeling and design of biomechanical products using CAx tools.

2. ASSEMBLY MODELING

Assembly models are mock-ups of a final mechanical product in assembly form. Each part of the product is modeled and then assembled together to create the assembly model. Assembly models are essential in design and allow designers to evaluate interferences of parts in the assembly, review and specify assembly procedures, review the relative motion of parts, and simulate product appearance. To assemble parts into an assembly model, mating conditions are specified and dictate how geometry or reference datums are constrained in order to hold the product together in a logical fashion.

In general, assembly modeling research focuses on three areas which include analysis and computer representation of assemblies [2],[6],[12-13],[17], the generation of sequences for product assembly [3],[10],[14],[16], and integrated assembly design utilizing several tools and techniques [4],[7-8]. This paper contributes to the analysis and computer representation of assemblies' area by allowing a new technique for assembly design for products that interface with the human body.

As in mechanical design, there are two theories in this particular area of assembly modeling. These approaches are the bottom-up and top-down methods to assembly modeling.

2.1 Assembly Model Theory

2.1.1 Bottom-Up Assembly Theory

In the bottom-up design approach, each part of an assembly is modeled separately and has its own internal and private variables. Relationships are not established between the separate parts at this stage of the design. After the modeling of each part is complete, the separate parts are then imported into and arranged in an assembly model. In the parameterization of a bottom-up designed product, shared dimensions can be referenced during modeling; however, the parts still have their own proprietary dimensions and variables.

2.1.2 Top-Down Assembly Theory

On the other hand, top-down assemblies begin with the definition of an assembly file which provides a global reference frame for all parts in the file. In our method, the body serves as the base part of the model. The relationships between the body and all of the components are well-defined before modeling anything on a CAD program. By utilizing this method parametric relationships can be defined before the parts are created. Figure 1 demonstrates the design of one of the components in a top down assembly process.

2.1.3 Mating Conditions

In assembly modeling, parts interface, or mate, with other parts in a definable way to create a product. These mating conditions are generally based upon shared axes, faces, or distances between two parts. Mating categories in traditional mechanical assembly modeling include contact, angular, or distance conditions. Although each category has several types of mating conditions, this paper will only introduce the basic concept of each. As the name suggests, contact constraints involve defining planes or axes on two separate parts that touch each other in some way. Similarly, distance constraints confine different parts to be a specified distance apart. Finally, angle constraints define an angle between key features on two parts. Generally, two or three of these constraints are used per part to fully define that part's position within the larger assembly. However, these traditional constraints were developed for prismatic parts, rather than for biomechanical parts. The following section develops modifications to the traditional mating constraints that facilitate biomechanical design.

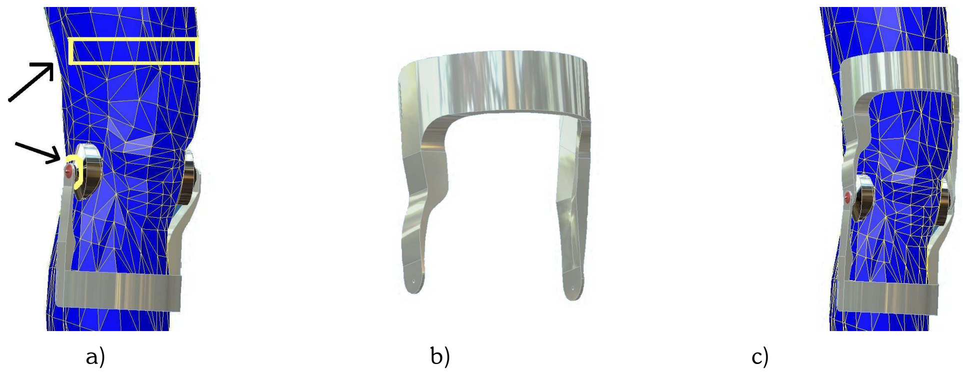


Fig. 1: Top Down Assembly in modeling a knee brace. a) Mating surfaces are identified on the existing parts and body for the top section of the brace. b) The top brace is modeled off of the interface by using parameters from the assembly model. c) The top brace is added to the assembly. [5].

2.2 Biomechanical Design Based on Assembly Model Theory

In biomechanical design, there must be a representation of the human body to accurately model products which interface with human surfaces. The body can be represented by using either anthropometric measurements, which reduce the body into parameter values, or through scanning techniques, which allow the creation of three dimensional human models. While anthropometric measurements are useful in many mass customization cases, they still lack the full definition of the interface surfaces. In this work, we combine anthropometric measurement techniques with 3D scans of human surfaces to create products that interface with the human body.

Although the representation of the human body with scans and anthropometric data can function as the base part in an assembly model, it is difficult to reference any mating parts to this reference geometry without defining datums in reference to the body geometry. Using recognized anatomical references from the medical field, the base part is annotated with datum planes which provide orientation references for later assembly work. Additional reference datums can then be made in reference to anatomical datum planes using anthropometric measurements. A fully articulated base model therefore consists of scan data representing the surfaces of the human body annotated with anatomical datums and any additional reference datums based off of appropriate anthropometric measurements. Figure 2 illustrates the recognized anatomical datum planes from the medical field and Figure 3 shows the base part of the human head annotated with recognized anatomical datum planes along with datum planes based on anthropometric measurements.

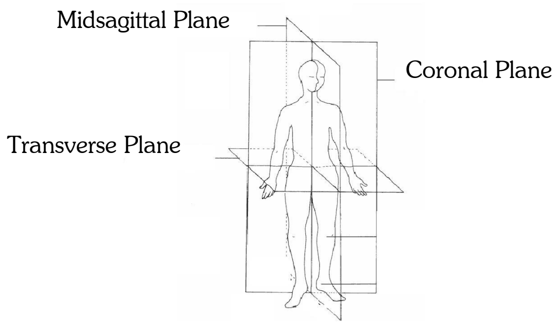


Fig. 2: Diagram of Standard Anatomical Planes [1].

The first step in biomechanical design is to import the annotated base part into an assembly model in a given CAD system. The next step in the process of a top-down design is to define the interface characteristics and criteria for mating parts. In principle, the mating conditions used in traditional CAD are similar to the mating conditions in biomechanical design. However there are some fundamental differences.

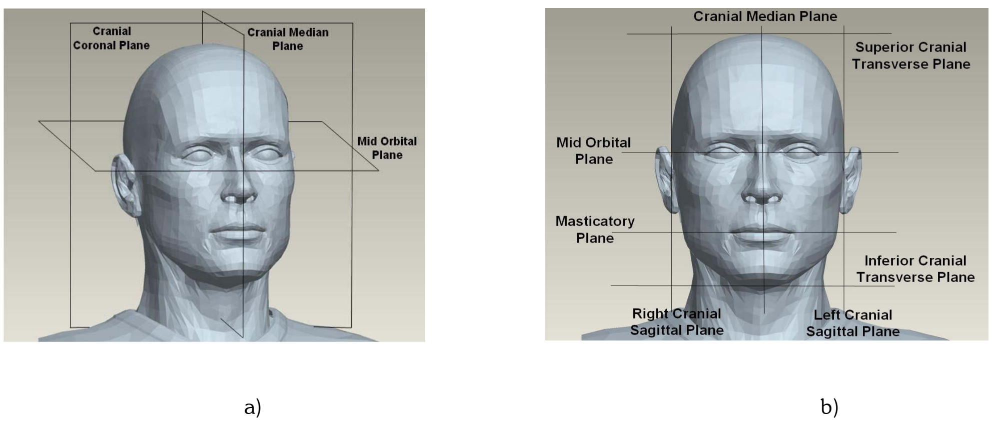


Fig. 3: Generic human head annotated with datum planes based on anatomical features and reference planes. a) Shows basic anatomical planes on the head. b) Shows additional planes based on anthropometric measurements.

Traditional assembly modeling focuses on three types of mating conditions: contact, angular, and distance, as mentioned earlier. However, these traditional mating conditions are specified for prismatic parts and not for interface with the complex surfaces of the human body. New classes of mating conditions must be defined for biomechanical assembly design.

2.2.1 Biomechanical Additions to Traditional Mating Conditions

In traditional design, there are three classes of mating conditions which were discussed earlier in this paper. Each class has its own subclasses that are used to further describe the organization of a designed product. However, because of the complex surface geometry of human surfaces, these traditional mating conditions are not sufficient to describe an assembly of a product that contacts the human body, or the interface conditions for the product-to-human interface. Consequently, new mating conditions must be specified to accurately model the product-human interfaces. The same general subclasses for mating conditions, however, will still be used. The additional conditions for biomechanical design will be added to each subclass, when necessary, to address biomechanical modeling needs.

In traditional mechanical design, contact conditions include the mate, align, and tangent mating conditions. Because these conditions address prismatic parts, contact conditions for biomechanical assembly design must also address three additional contact options: surface contacts, curve contacts, and point contacts. In surface contacts, entire complex surface areas contact each other. Since human body surfaces are compliant and will change slightly when force is applied, the surface contact must be prescribed in relation to a force per unit area experienced. The second type of contact mating is the curve contact. In this case, a narrow surface or curve of the geometry contacts the human surface. Finally, point contacts occur when a small surface or a point contacts the human surface. In traditional design, it is possible to align axes, datums, and surfaces. In biomechanical design, these conditions are valid with respect to datum axes of the human body and the anatomical datum planes of the body. There are no additions needed to the align subclass of contact mating conditions.

The tangent subclass consists of the mating of points or curves along a surface. In biomechanical design, the complex human surfaces may sometimes contact products along a line, curve, or surface. However, because this is similar to the additions in the mate subclass, there is no need to add additional conditions under the tangent subclass.
Angular mating conditions consist of an axis and a rotation. For biomechanical design, this can be done on a datum axis of the human body. Additional conditions for the angular class are not needed.

The final mating condition class is the distance class. In traditional design, this mating condition specifies the distance between two prismatic faces or the distance from a datum. In biomechanical design there are additional distances that need to be specified in order to define the assembly of a product to the human body. These conditions include the following distances:

- Point to point
- Point to curve
- Point to surface
- Curve to curve
- Curve to surface
- Surface to surface

Table 1 summarizes current assembly modeling mating conditions as well as the additional mating conditions needed to address biomechanical design. Though the necessary mating conditions for biomechanical design have been defined in this paper, they have not yet been implemented in any CAD system.

3. ASSEMBLY DESIGN TECHNIQUES

An important characteristic of assembly models are the appropriate geometric relationships between parts. These relationships include the degree to which the mating conditions are met, such as gaps present between parts in the assembly, the proper alignment of components, and how parts mate together. These geometric relationships must be established to allow the creation and assembly of a product as well as the parameterization of the product through the creation of reusable assembly models.

Mating Condition Classes	Traditional Mating Condition Subclasses	Biomechanical Mating Condition Subclasses
Contact	Mate	Surface Contact
	Align	Curve Contact
	Tangent	Point Contact
Angular	Parallel	
	Perpendicular	
	Custom Angle	
Distance	Center	Point-to-Point
		Point-to-curve
		Point-to-surface
	Distance	Curve-to-curve
		Curve-to-surface
		Surface-to-surface

Tab. 1: Specification of Classes and Subclasses of the Mating Conditions necessary for Biomechanical Design.

Whitney et al. [21] describe a process for designing assemblies that utilizes geometric relationships and assembly features to achieve kinematic constraints over an entire assembly. In this process, geometric relationships are defined between parts and referred to as Key Characteristics (KCs). KCs define important relationships between parts, such as clearances, where failure could result if KC's were not followed [11],[20]. The arrangement of these KCs and the assembly features between parts define the Datum Flow Chain (DFC). An assembly feature is a link between parts that do not have mating conditions where key characteristics are not required.

This theory lends itself well to the biomechanical assembly design process. Because of this, this assembly model method will utilize some of these techniques to articulate customizable biomechanical devices. Key characteristics and assembly features will be defined between the parts of the assembly, where the human scan data is recognized as the base part of the assembly. These KCs and assembly features are used to create a datum flow chain for biomechanical products that utilize human data as the base part of the assembly.

4. PARAMETRIC STRATEGIES FOR MASS CUSTOMIZATION IN BIOMECHANICAL PARTS

The traditional mechanical design method uses a sequence of steps to create a product based on customer inputs. These steps are useful in planning, management, design, quality assurance, and the coordination of the product development process. In order to create a biomechanical process that is familiar to engineers, the steps for biomechanical design are integrated into the traditional design method described by Ulrich and Eppinger [19]. The steps of this methodology are listed next.

1. Planning
2. Concept Development
3. System Level Design
4. Detailed Design
5. Testing and Refinement
6. Production Ramp Up

Biomechanical assembly modeling techniques need to be integrated into this traditional design method to allow for the creation of reusable models that ultimately allow for the mass customization of products that interface with the human body. In order to allow for this capability, the traditional design methodology is altered to include the following sub-steps that are demonstrated on a ski goggles example. The design strategy for articulating a customizable product that interfaces with the body is as follows:

1. Planning
2. Concept Development
    a. Geometric Configuration
3. System Level Design
    a. Liason Diagram
    b. Mating conditions
    c. Parametric Strategies
    d. Feature Structure
4. Detailed Design
    a. Bio-reference definitions
    b. Product geometry creation
    c. Parameterization
    d. Mass customization
5. Testing and Refinement
6. Production Ramp Up

4.1 Planning and Concept Development

In the planning and concept development phases, the business strategy, an overall view of technologies in the target market, and the identification of the needs of the target market are identified. The evaluation of the product ideas and a concept selection is made. In biomechanical design, these steps do not change. A concept would be identified and evaluated. In the assembly model method, the interaction of the concept to the body and to other components of the design is defined. This can be seen for a pair of ski goggles shown in Figure 4.

4.2 System Level Design

In system level design, the geometric configuration is further developed to specify the Key Characteristics of the assembly. These KCs are represented in a liaison diagram [20-21]. Following the articulation of the liaison diagram, the diagram is analyzed in order to define the mating conditions, parametric strategies, and the bio-references that will be used to define the feature structure of the product.

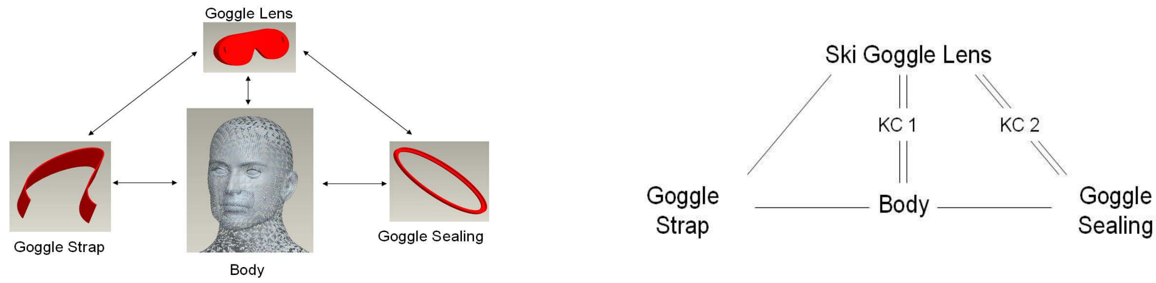


Fig. 4: Concept Development of Assembly Design. a) Components are identified in a **Geometric Configuration Schematic**. b) A **Liaison Diagram** specifying Key Characteristics and Assembly Features for Ski Goggles Design.

As stated in [20], the liaison diagram specifies the geometric relationships of the assembly model. Key characteristics are represented with a double line, while assembly features are represented by a single line. In the ski goggles example, the lens must be modeled to fit the human scan data using specific geometric relationships, requiring a KC. In addition, the rubber goggle sealing must properly fit with the ski goggle lens in order fix its position in the assembly and create a seal making a second key characteristic necessary. Where KCs are not essential but parts are still assembled, assembly features exist, such as the relationship between the lens and the strap, the body and the strap, and the sealing and the body. Because the strap and the goggle sealing are flexible and conform to the body, KC's are not required to define their relationship. Figure 4 illustrates the key characteristics and assembly features for the ski goggles example.

Following the specification of the liaison diagram and the parts with key characteristic relationships, these key characteristics must be articulated in terms of mating conditions in order to define the parametric strategies for the device. Table 2 describes the key characteristics and mating conditions for the ski goggles example.

KC	Description	Mating Conditions
1	Goggle Lens to Body	Surface Contact
2	Goggle Lens to Goggle Sealing	Contact (traditional mating condition)

Tab. 2: Description of Key Characteristics and associated mating conditions for ski goggles example.

With the mating conditions defined, the designer can then analyze these mating conditions to determine the parametric strategies for the product. Parametric strategies have been applied to traditional mechanical design to allow for mass customization. Traditional parametric strategies focus on identifying a small set of key parameters upon which all parametric relationships are based [18]. When this strategy is employed, an entire design can be updated as the key parameters are changed. To apply parametric strategies to biomechanical design, anthropometric measurements and datum points based on points on the human surface become the key parameters. As these key parameters are changed to represent a new person, the product design can be updated to accommodate the individual's unique measurements and surfaces. In this research, a template model of human data was used. As mass customization is explored in the future, this template model would be replaced by data from scanned individuals, or changed to fit the surfaces of a scanned individual.

Table 3 specifies the parametric strategies for the ski goggles design that are associated with the identified key characteristic. There are other parametric conditions for the ski goggles, such as allowing the lens to adjust to the width of the face, however, these types of parametric conditions do not deal with mating conditions and are not addressed in this paper.

KC	Mating Condition	Parametric Strategy
1	Surface Contact	Lens Extrusion: Create reference surface for geometry creation by establishing datum points and curves on Human scan data. Extrude lens sketch to the parametric surface to create surface contact
2	Contact	Negative Sweep for sealing channel: Create trajectory for channel that is offset from sketch for lens extrusion. The Channel must maintain offset distance despite changes in frame due to different human scan models. Sweep cross-section referenced to fit sealing.

Tab. 3: Parametric strategies and descriptions associated with Key Characteristics.

These parametric strategies help dictate the bio-datums necessary for appropriate mating conditions that must be defined for geometry creation. These bio-datums allow for the definition of the feature structure of the device. The Feature Structure decomposes the product into the basic primitives of solid modeling that are used in geometry creation [15]. These features include revolutions, extrusions, sweeps, and blends. In this method, the key characteristics lead to the definition of the mating conditions and parametric strategies. In turn, these parametric strategies allow the designer to easily determine the bio-geometric references required to satisfy the parametric strategies. With these references defined, the product can then be decomposed into the solid modeling operations and the product feature structure can be defined. In the feature structure, all datum references, sketches, and features are clearly defined in order to easily create the geometry of the device. Figure 5 shows a simplified feature structure for the ski goggles design.

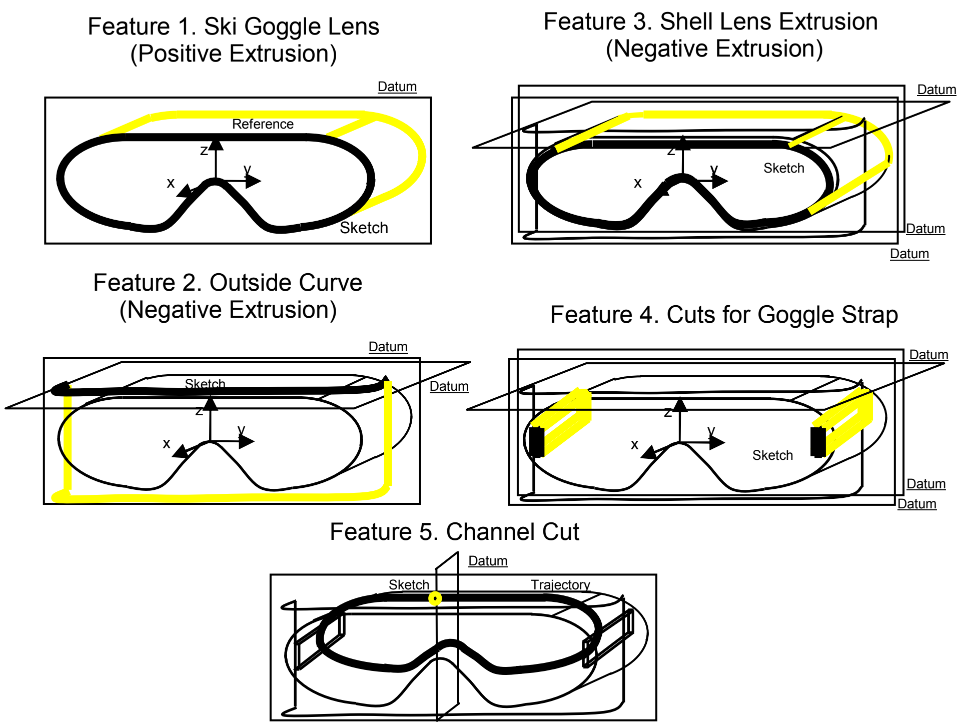
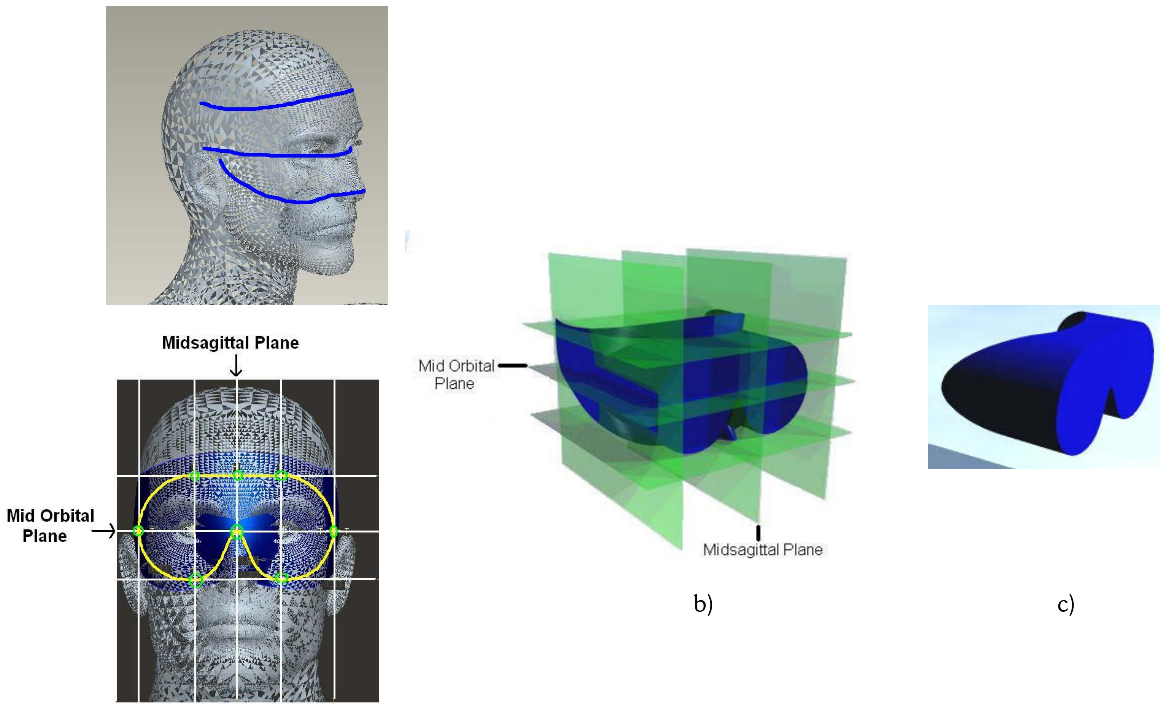


Fig. 5: Feature structure of ski goggles design.

After the feature structure is identified and the product design is planned, the designer is now ready to create the appropriate bio-datums on the human scan model in the CAD system and create the geometry for the product in the detailed design phase of the design process.



a)

Fig. 6: Geometry creation for goggle lens frame. a) First, datum points are defined on the surface of the scan data (top) and datum planes are defined in relation to key points (bottom). b) A parametric model is defined utilizing the points and surfaces defined in part a. c) Finished lens extrusion.

4.3 Detailed Design

The detailed design phase of the design process includes the creation of bio-references, geometry creation, parameterization, and mass customization.

In bio-interface design, the key characteristics identified in the liaison diagrams are further developed and defined by creating the appropriate bio-datums and references on the scan data within the CAD system. The creation of these references allows for geometry creation and the parameterization of the product model. After the references have been created on the scan data through the use of datum planes, datum axes, and datum points, the product can be modeled using solid and surface modeling techniques. Geometry creation of the ski goggles is illustrated in Fig. 6.

After the geometry has been created, the product can be parameterized to allow for the mass customization of the designed product. In parameterization, key parametric variables are specified and related to each other through constraint equations. In biomechanical design, these variables are relationships between the product geometry and the scan data and often take the form of dimensions to the bio-datum planes and references. This will allow the product to change depending on the shape of the human scan data. By entering the new distances between bio-datums, the model regenerates to fit the distances.

Finally, with the parameterization in place, mass customization can be explored. Referencing bio-datums and bio-points allows for key characteristics to be maintained. Scan data for different individuals can be taken and applied to the product model by using the same references identified in the template scan data. With the application of new scan data to the product, the product model can regenerate to fit the references and dimensions of the new person either automatically or manually by entering new reference dimensions.

5. SUMMARY AND CONCLUSIONS

This paper presents a method of design that allows for the articulation of customizable products that interface with the human body. The core of this method is the definition of biomechanical products as an assembly model, where human data is defined as the base part. This paper expands on traditional mating conditions in assembly theory by identifying different ways products can interface with the human body. With the identification of these mating conditions, products can be designed to interact with the body in definable ways through the definition of parametric strategies.

This paper also outlines a design process for the articulation of biomechanical designs through the addition of design steps to the traditional mechanical design process that meet the needs of biomechanical design. By using this process, the interaction between the product and the person can be easily defined through key characteristics. Using these key characteristics, bio-references can be defined that allow for the creation of the product using traditional CAx tools. Parametric strategies can then be applied to biomechanical devices, allowing for the exploration of mass customization for products that interface with the human body.

6. REFERENCES

[1] Anthropology CSU Sacramento: skeleton-anatomical plane website, http://www.csus.edu/anth/physanth/BONES%20HTM/18_anatomical%20plane.htm (accessed March, 2006).

[2] Cunningham, J. J.; Dixon, J. R.: Designing with features: the origin of features, 1988 ASME Computers in Engineering Conference, San Fransisco, ASME, 237-243.

[3] DeFazio, T. L.; Whitney, D. E.: Simplified generation of all mechanical assembly sequences, IEEE Journal of Robotics and Automation RA-3(6), 1987, 640-658.

[4] Eversheim, W.; Baumann, M.: Assembly-Oriented Design Process, Computers in Industry, 17, 1991, 287-300.

[5] Fisher, J.: ME 172 Semester Project, Fall 2006, Brigham Young University.

[6] Gui J.; Mäntylä M.: Functional understanding of assembly modeling, Computer Aided Design, 26(6), 1994, 435-451.

[7] Hsu, W.; Lee, C. S. G.; and Su, S. F.: Feedback approach to design for assembly by evaluation of assembly plan, Computer Aided Design, 25(7), 1993, 395-410.

[8] Huang, Y. F.; Lee, C. S. G.: A framework of knowledge based assembly planning, IEEE Conference on Robotics and Automation, Sacramento, CA, 1, April 1991, 599-604.

[9] Jensen, C. G.; Tucker, S. S.; Jones, C. L.; Tomikashi, M.: Parametric Engineering Design Tools and Applications, Proceedings of the 2000 Design Engineering and Technical Conferences, Baltimore, MD, 2000, DETC 2000/DAC-14275.

[10] Ko, H.; Lee, K.: Automatic assembling procedure generation from mating conditions, Computer Aided Design, 19(1), 1987, 3-10.

[11] Lee, D. J.; Thornton, A. C.: The Identification and Use of Key Characteristics in the Product Development Process, Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, August 18-22, 1996, Irvine, CA, DETC 96/DTM-1506.

[12] Lee, K.; Gossard, D.: A hierarchical data structure for representing assemblies: part 1. Computer Aided Design, 17(1), 1985, 15-19.

[13] Mäntylä, M.: A modeling system for top-down design of assembled products, IBM Journal of Research and Development 34(5), 1990, 636-659.

[14] Mello, L. H. D.; Sanderson, A.: A correct and complete algorithm for the generation of mechanical assembly sequences, IEEE Journal of Robotics and Automation, 1989, 56-61.

[15] Pool, T. C.: Product Templates: A Parametric Based Approach to Product Development, Masters Thesis, Brigham Young University, Provo, UT 1998.

[16] Romney, B.; Godard, C.; Goldwasser, M.; Ramkumar, G.: An Efficient System for Geometric Assembly Sequence Generation and Evaluation, ASME International Computers in Engineering Conference, Boston, ASME, 1995, 699-712.

[17] Shah, J.: Conceptual development of form features and feature modelers, Research in Engineering Design, 2, 1991, 93-108.

[18] Shah, J. J.; Sen, S.; Ghosh, S.: An Intelligent CAD Environment for Routine Mechanical Design, Computers in Engineering, 1, 111-117.

[19] Ulrich, K. T.; Eppinger, S. D.: Product Design and Development, third edition, McGraw-Hill, Inc. New York 1995.

[20] Whitney, D. E.: The role of key characteristics in the design of mechanical assemblies, Assembly Automation, 26(4), 2006, 315-322.

[21] Whitney, D. E.; Mantripragada, R.; Adams, J. D.; Rhee, S. J.: Designing Assemblies, Research in Engineering Design, 11, 1999, 229-253.

[22] Ziolek, S. A.; Kruithof P. C.: Human Modeling and Simulation: A Primer for Practitioners, Proceedings of the International Ergonomics Association and the 44th Annual Meeting of the Human Factors and Ergonomics Association, July 29-Aug 4 2000, 825-827