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ERGONOMIC DESIGN AID FOR HAND-HELD PRODUCTS

K.Case and R.Harwood

Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leics, LE11 3TU, UK

ABSTRACT

As modern consumer products reduce in size and gain in technology there is an increasing need for ergonomic design. Additionally, ergonomics in manufacturing is increasingly an issue due to problems with the postural impact on work tasks (for example strain injuries). Traditional design practices may consider ergonomics at the later stages of design, but by then heavy investment may have already been committed to the design or manufacturing planning, reducing the impact of any ergonomic decisions. Attempts are made to address this ergonomics implementation problem through three-dimensional computer modelling of the hand.

The hand's biological structure is first explored and simplified before application of biomechanical principles. Anthropometric data is combined with biomechanical methodologies so that an internal bone structure can be fully defined dimensionally. Modelling this bone structure is seen to be extremely complex and a simplified model is produced that represents the major characteristics of the link and joint system. Skin has been modelled over this skeletal structure through surface modelling based on point cloud data obtained from a three-dimensional scanner. Articulation of the joints of the hand are explored through use of the mechanism facilities of the underlying CAD modeller (Unigraphics) and by methods relying more heavily on user interaction.

The hand model integration with the CAD system allows the ergonomic evaluation to be carried out as part of the normal design process and examples of this in mobile phone and drinks' can design are provided as a case study.

1. INTRODUCTION

The design of a hand-held product requires the consideration of ergonomics aspects as well as form, function and materials. Failure to consider ergonomics can reduce the product's marketability and can lead to fatigue or repetitive strain injuries when operating the product for long periods of time. Often these problems have been associated with industrial work where high loads, impacts and frequencies are regularly employed. However, as electronic products reduce in size and cost, a new generation of technologically minded consumers use their hands for more complex and intricate operations.

Traditionally, designers have to wait for the first prototype production to evaluate the product-hand interface. At this stage, heavy investment will already have been committed in tooling, rendering any further ergonomic changes to the design expensive and perhaps impractical. Clearly, the designer must be confident with the product's ergonomics before costs are committed and a CAD simulated hand is proposed for use with conventional CAD systems for product realisation.

In this research a Unigraphics CAD model is created with the main objectives being to use anthropometry and biomechanics data available from the literature [1]. The emphasis is on the general form, shape and articulation of the hand rather than graphical and animation realism.

2. BACKGROUND

Life-like animation research is relevant to this work. A good example is found in [2] which describes modelling the human hand by considering dynamics and natural motion constraints. Inter-dependencies between individual bones are used to eliminate un-natural motion. An internal dynamic bone structure is constructed and driven by inverse kinematic algorithms. Natural posture mapping is achieved by considering the constraints acting on segments of the hand. These include motion restrictions due to the structure of the joints, articulation order when bending the finger, and the binding properties of skin. Un-natural constraints can be said to add 'potential energy' to the structure, i.e. the structure is strained and wishes to return to a more natural position. Assigning 'virtual' springs to the joints creates a rigid structure whilst emulating this potential energy or 'unwillingness' to hold a position. A skin for the model was created by digitising a 3D plaster mould of the hand which was converted into a polygonal surface model and overlaid onto the internal structure. Corresponding nodes were positioned on the skin's surface and internal bone structure, in the relaxed hand position. Algorithms were then defined to check the relative positions of the bone and skin nodes. Alterations to the skin position as a bone is articulated was handled by 'virtual' bonds.

Many mathematical models of the hand can be found in biomechanics research [3,4,5]. For each structure within the hand, details of individual muscle forces, point of origin and action are described, possibly allowing the estimation of stress and strain on individual muscles. In particular, [4] describes the results and a measurement methodology to calculate the flexion angle, angular velocity and angular acceleration of the finger. In [5] a methodology is described for measuring ranges of motion, joint angular velocity and acceleration. Volumes, mean fibre lengths and cross sectional areas are calculated to estimate a muscular centroid force. Combining moment arm information with these forces allows the effects of each muscle to be calculated, with respect to motion and could,be used for a quantitative analysis of individual muscles.

Finally, hand motion capture researchers are currently trying to implement and refine computerised hand gesture recognition software [6], requiring the recognition of the orientation and configuration of a hand from a single image.

3. BIOMECHANICS OF THE HAND

The structure of the human hand is very complex due to the large number of bones and their articulation systems and there is a need to simplify its structure and in particular to focus on the exterior surfaces as these are of interest in the 'fit' of an object in the hand. However, it is has been found [2, 6], that the use of dynamic internal structures, simplifies the articulation and improves accuracy. The axis, direction and range of movement can be geometrically defined by the operator if the internal structure is modeled in a CAD system.

The hand contains three major groups of bones (see figure 1); the phalanges (distal, middle and proximal), the metacarpals and the carpals. The phalanges play the most important role in the hand's grip. Large ranges of motion provide high manoeuvrability and, when combined with the rest of the hand's function, can form a very adaptable

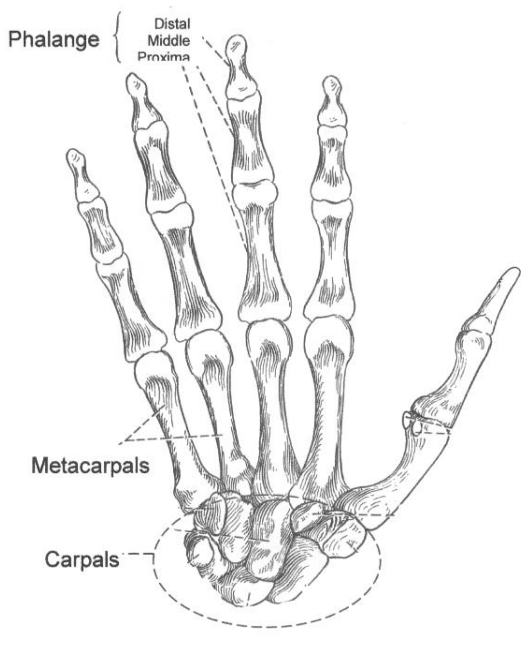

Figure 1. Bone Structure of the Hand

grip. The carpal bones are responsible for the manoeuvrability and large range of movement of the wrist, and the metacarpals play a significant part in the 'cupping' motion of the hand. Although they are bound by skin and ligaments in the body of the hand, their motion contributes to the concave and convex palmer motion.

The hand contains a large number of joints. The wrist itself consists of four major joints. The carpometacarpal joint comprises two sockets, one for the fingers, another for the thumb. The five joints are connected by tendons to the intermetacarpal joints and the distal row of carpals. The metacarpophalangeal joint is situated between the metacarpals and proximal phalangeal bones, and allows flexion and extension and slight movement side to side. The interphalangeal joints mainly provide flexion and extension of the hand, but slight rotation along the length of the finger is permitted.

Articulation of the individual bones is restricted by four factors, bone shape, tendon origin and vector of motion and cross-joint ligaments [7]. Examining the *effects* of these factors is much more valuable than studying each interaction individually, and this is achieved by classifying joints as hinge, saddle, gliding and ellipsoidal joints. Hinge joints are found in the distal joints in the fingers which can only flex and extend (i.e. motion constrained to one plane). A three degree of freedom saddle (or universal) joint can be found between the trapezium and the first metacarpal. The carpals only undergo planar slipping and sliding motion and can be modeled as gliding joints. Joints between the metacarpal and phalange of the finger permit two axes of motion, flexion-extension (extensive to allow gripping) and adduction-abduction (severely limited by ligaments to prevent the knuckles from spreading apart) and can be represented as an ellipsoidal joint.

Whilst the kinematic structure may be considered as being constant between individuals (unless the hand has sustained damage), anthropometry (size and shape) will vary in ways that are extremely important for design. For this work external data from [1] was used and mapped to determine dimensions of the internal structure – this is a complex process, a description of which is beyond the scope of this paper.

4. CAD MODELLING

Solid rather than surface modelling has been chosen for the bone structure and a skin surface model is wrapped over the bones, reducing or eliminating the visibility of the underlying structure. Early work modelled bones with something approaching a realistic shape, but a simplification strips all unnecessary form from the structure but maintains anthropometric and functional geometry. A sphere at the tip of the bone houses the joint whilst the base is extended to allow pivoting from the centre of motion (located in the head of the adjacent proximal bone). The bones and joints were assembled to form the skeletal system using a hierarchical structure comprising assemblies and sub-assemblies. Components were added and mated from the tips of the fingers down to the wrist; with each mating condition constraining joints to their respective degrees of freedom.

Modelling accuracy needs to be confirmed before the skin model can be created and stretched over the internal structure. Assembly drawings of each finger structure were dimensioned and printed to evaluate both individual bone lengths and total system lengths. Nearly eighty percent of the internal structure was dimensioned correctly, most of the inconsistencies being found round the Hooke's joint at the knuckles. Any errors were fixed for individual bones with the aim of reducing the total system error when compared with normalised x-ray and anthropometric data.

A skin surface model is now required to wrap over the internal structure. Numerous options for obtaining the initial hand form were possible including MRI scan data, 3D laser scanner data and importing existing CAD models. Medical data proved troublesome for several reasons and so a 3D laser scan based on a plaster cast was used to generate a cloud of points. This cloud of points could then be used in Unigraphics or other surface software to construct an editable skin model ready to be attached to the internal system. Different surfacing techniques were available. The cloud of points could be simply converted into a tessellated form but this does not give true solidity which could cause problems when attaching the skin to the internal structure. The chosen solution was a NURBS surface model as it gave a high degree of adjustability and an accurate reproduction of point data into a ‘solid’ model. Creating a surface in this way is not trivial and various techniques within a number of proprietary surface modellers were used. Figure 2 shows a preliminary skin model (with split lines for ease of modeling).

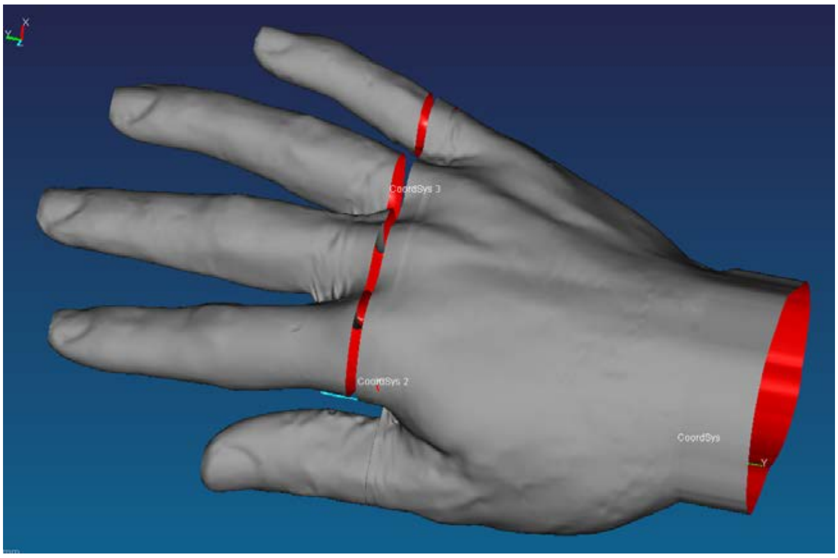

Figure 2. Preliminary skin model (showing splitting)

Before the skin can be split at its joints, the surface needs to be scaled and fitted to the internal bone structure. Accuracy of split location is important on the outer skin and must match the internal structure. A perfect match will be made if the internal geometry is used to locate and orient this splitting plane and achieving this involved a considerable amount of ‘trial-and-error’.

Motion of the skin surface during articulation is an important factor in this work. The use of dynamic and elastic skin properties, although ideal, was far beyond the scope of this work. Functionality is also more important than photo-realistism, so the emphasis was on accurate *static* surfaces on the *palmer* side of the hand. Therefore, any cracks appearing on the dorsal (upper) surface are of no functional concern. Three solutions were initially considered; interlocking plates (cf armour), skin trimmed to a larger spherical joint (uniform skin motion over an underlying sphere) or split and modify cracks by closing a surface over the gap.

Although the possibility of using interlocking and sliding plates provides the most accurate solution, the modelling would be correspondingly complex. The second possible solution relies on centrally located spheres (finger joints) to provide a uniform gliding surface. However, cross-sectional form at the joints is neither uniform nor circular, increasing the difficulty of fitting a sphere.

Both previous solutions focus on skin motion on the fingers, but the third solution tries to solve palmer skin motion, an important factor of grip comfort. Splitting the palm cloud in the same orientation as the bones will allow more realistic skin motion as each bone is articulated. However, a simple surface split operation would create cracks when the skin is parted. Ideally, realism could be increased by removing these cracks and giving the hand a solid appearance, in any orientation. Although solidifying the hand is impractical, the user could possibly be fooled into recognising a solid transition between different skin sections. Filleting the gaps or surface edges to each other would give this impression; however, a 'real-time' filleting algorithm would have to be implemented which was impractical for this work. The solution, therefore, was to close the gaps created from splitting the palm, creating individual 'pods' within which the bone could articulate. The curved, closed surface would also provide a smooth transition between the two surfaces when they are separated.

When considering the motion a hand undergoes when forming a grip on a product four distinct types of motion may occur:

- *Position and Orientation* - rotation and translation of the whole hand at the wrist.
- *Natural motion* - groups of bones articulating individually to replicate natural motion e.g. curling fingers, flattening hand, spreading fingers etc.
- *Individual bone motion.*
- *Grouped bone motion* - groups of the same type of bone rotating e.g. finger tips.

Position and Orientation. Before the hand is able to form a grip on the product, it must first be correctly oriented and positioned with respect to the product. This is most simply implemented by utilising the translate function from the assemblies module of Unigraphics.

Natural Motion. Motion mapping of the hand when in day-to-day use, can identify certain patterns frequently used when forming a grip on an object. This is identified as natural motion and for the purposes of this research includes; curling fingers (finger is flexed, bones articulate in proportion to their order; the finger tip is always articulated to the highest degree), cup and flatten palm (metacarpals move proportionately to the distance from the centre of the hand): spread fingers (fingers and thumb spread from the centre; little finger and thumb articulate at twice the rate).

Implementation was achieved through simple algorithms to proportionally increase or decrease a joint's angle. Motion for cupping and flattening the palm can be created simply by articulating the phalanges first followed by the metacarpals. This motion is restricted to a certain degree as the skin for the three middle metacarpals is bound together. Spreading the fingers apart proportionately can be achieved in a similar fashion to the finger curling.

Individual and Grouped Bone Motion. This refers to individual bone motion and the motion of similar bones in different structures, e.g. articulate all fingertips by 5°.

5. CASE STUDY

To articulate one's hand in reality is second nature. Achieving a static position, where touch is the overriding sensory input, requires less conscious thought than a dynamic interaction where greater hand-eye co-ordination is required. Sensory information relayed to the brain from the hand greatly simplifies the task of gripping an object; without this information the task becomes very difficult. Whilst in real life sight guides the positioning of the hand in 3D space, only a 2D perspective of a 3D space can be achieved through CAD. This is further exacerbated. by a complete loss of touch, increasing the difficulty of recognising hand and objects clashing. Implementation of algorithms could solve many of these problems, but the created hand model does not currently utilise these features.

A model of a mobile phone was loaded into the hand assembly, and then rotated and translated by 'click-and-drag', through the 're-position components' function. Difficulties were found when trying to achieve the correct orientation of the phone with respect to the hand. In reality, an object is oriented to the most comfortable position through a combination of touch and the object's inherent solidity. As a designer using the software, one must guess a comfortable position then use trial-and-error to match the phone's surface to the palm of the hand. Digit articulation started with the little finger and progressed through to the index finger. Utilising the 're-position component' function with 'click and drag' greatly simplified the operation, and proved a much quicker method to use than any incremental method. Positions one could consider as comfortable, were finally achieved with little difficulty. Recognition of the skin touching the phone was through utilisation of either a wireframe display or frequent manipulation of the shaded display. Frequent re-orientation of the phone had to be achieved, as the skin surface changed shape as individual structures were moved. Re-positioning the hand to form a grip on the phone took a considerable time. Repetitive and time consuming selection of the joint centres required a large portion of this time. Automatic assignment of the joint centres depending on the selected bone would further reduce this process time.

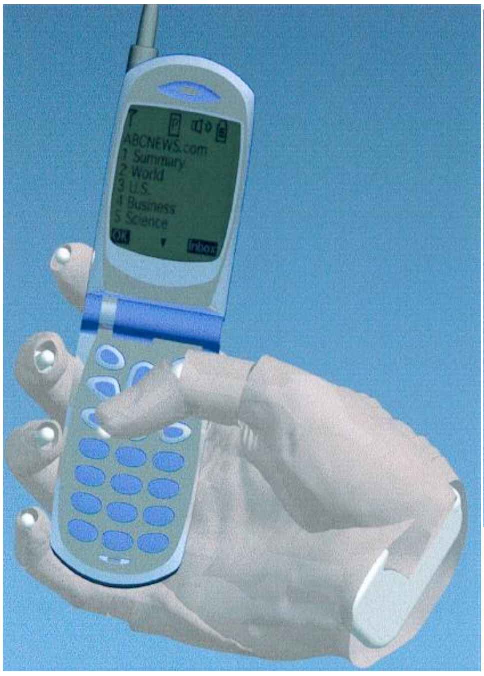

Figure 3. Mobile Phone Evaluation

The Unigraphics hand model would considerably help during the initial stages of the design of the phone. A better comprehension of the size and scale of the phone is given and alternatives can be quickly assessed through re-scaling the model. Through careful manipulation of the view, the phone-hand interface can be used to visually assess the 'snug' or 'loose' fit. Indeed, a further approach to evaluating this comfort level can be achieved though a wireframe view, assessing the amount of 'overlap' or clashing between hand and phone.

Comfort requires unity of a product's form to the hand's palmer surface; for example, sharper more angular shapes feel uncomfortable when gripped by the hand. Cross-sectioning the hand at each fingertip, when gripping an object, allows the designer to assess the difference in shape between the product and hand. This interface should be similar in form and smooth as possible to provide the most comfortable grip. Assessing the mobile phone in such a way highlights its un-ergonomic, rectangular form, but would provide the designer with an excellent tool to modify its exterior case.

Although dynamic object interactions cannot be analysed, the static positions of these dynamic actions can certainly be explored. For example, it may not be possible to assess the comfort, or grip when keying a number; it is however, possible to confirm that all buttons can be reached when keying. Through simple 'click-and-drag' operations, the thumb was moved to the extents of its working envelope. A design fault was identified from this; three buttons at the bottom left of the keypad were badly positioned and appeared to require strained positions. Figure 4 shows a similar evaluation of a drinks’ can.

Overall the hand model performed well when evaluating the phone and drinks can, and the only issue which still remains to be discussed is the lack of quantative results. A designer's perspective of ergonomic qualities varies from person to person, and sector to sector. A designer's decision on a comfortable grip using this software, for example, could be based on clouded judgement rather than correct use of the model. Results gained from this software are qualitative and can therefore be interpreted in a number of ways. Further work could explore the use of algorithms and a mechanical system, which could be overlaid onto the current system to provide a quantative solution. This may range from a 'go', 'no-go' situation to 'highly comfortable', 'comfortable', 'uncomfortable' or 'strained'. A reduction in user oriented ergonomic decision making should standardise the achievable results using this package.

Figure 4. Drink’s Can Evaluation

6. CONCLUSION

A hand model has been successfully created within a proprietary computer aided design system and some indication given of how it can be useful in the design of hand-held products.

Freely available anthropometric data was used in constructng various aspects of the shape, form and dimensionality of the various components of the hand model. Articulation through the use of Unigraphics Motion module was achieved; however, the system could only sustain certain types of motion. Menu articulation, therefore, lay with the application of the Assembly modules 're-position components' function. The resultant control the operator has over the hand was more difficult than anticipated as a simple to operate user interface has not been implemented. The final design considered four different types of motion the operator could initiate including grouped motion and natural motion through variable angles.

A functional evaluation of the hand provided a chance to asses the quality of results which can be achieved. Through cross-sectioning the fingers, one can assess the product-hand interface to check the skin's conformity to a grip. This could be especially useful for products whose performance relies heavily on their owner's grip, such as golf clubs for example. A huge benefit could be gained by the power tools industry, especially hand-held tool manufacturers. There is considerable complexity in designing a powerful tool that combines all necessary parts into an easy to operate hand held product. Initiating the hand model during the early stages of design for these products could drastically reduce possible re-work time and aid integration of the technology around the hand. The ability of a designer to load a 3D hand at any time allows frequent visual verification of a design during style 'tweaking'.

The ability to verify the working envelope of each digit may be useful when applied to the electronics manufacture of small hand held components. Analysis of the mobile phone, for example, showed that three buttons were poorly placed. Other products include the new generation of hand held personal organisers or games machine joypads. All of these products require buttons which can be accessed with the minimum of effort, without major re-positioning or straining of the hand.

The research aimed to utilise standard ranges of motion for the hand, replicating natural constraints. Initial planning led to the conclusion that geometrically defined joints would allow the use of clash detection within the motion module. However, it became clear as the skin structure was overlaid that the clash detection system would highlight clashes of the skin prior to internal joint geometry clashes. Ranges of motion were therefore left undefined.

The latest fashion and design trends lead to out-of-the-ordinary styles and novel approaches to interaction with a product. This hand tool should enable the designer to consider their clients' comfort needs at the beginning of design, before projects costs are committed.

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