GOAL DEFINITION SPREADSHEET FOR THE DESIGN OF A DAMPED WRIST ORTHOSIS

by

David T. Wimberly Jr.

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Signature of Author ______________________
Department of Mechanical Engineering
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Certified by ______________________
Dr. Michael J. Rosen
Thesis Supervisor

Accepted by ______________________
Professor Peter Griffith
Chairman, Department Committee

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Abstract

A design method using an electronic spreadsheet is studied. Using the problem of designing a damped wrist orthosis for persons with tremor, a spreadsheet is written that evaluates how well the goals of the design are met by proposed designs. In depth description of the process of preparing such a spreadsheet is presented. Preliminary designs are evaluated with the developed spreadsheet and conclusions about this type of design process are discussed.

Thesis Supervisor: Dr. Michael J. Rosen
Title: Principal Research Scientist

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Chapter 1

Introduction

1.1 The Design Process

Engineers involved in mechanical design must thoroughly carry out the complicated task of creating an object which meets conflicting goals and constraints. Whether working in a large firm or for oneself, the designer will have specifications coming at him from different directions. There will be needs that involve marketing the product such as its cost, competitiveness and time frame of production. Basic functional issues such as what the product will accomplish, who will use it, what it can look like and what it can not look like will also need to be addressed. In many cases these constraints will be defined by different people or departments within a company, be expressed in different terms and not be equally important.

These issues will usually be complicated and difficult to keep track of. Besides being poorly defined and hard to express in easily evaluated units, the many desires or objectives of a project will oppose each other. In order to meet one objective well, it may be necessary to sacrifice other objectives. The designer must come up with many ideas for solutions to the problem and each idea must be evaluated against the goals and constraints set down in the problem's objectives. It is very difficult to keep track of all of the issues involved when evaluating the proposals, so that oftentimes only the main issues get considered.

Some design methodologies are meant to foster the creativity of the individual to help him/her generate as many solutions as possible. Usually the designer is left to his/her expertise to interpret or estimate the performance of each proposal and choose the best one. This always involves lots of revision and iteration if the designer is doing a thorough job, since much is learned from suggesting many different solutions and trying to develop them according to how well they achieve the various goals and objectives. Two of these methods that are fairly well known are Pugh's Concept Selection[1], EDK 5 Paper M3/16, pp497-506) and The House of Quality[2], pp63-73).

Such existing methods of design would be greatly improved if there was a way to make the process of evaluating the different proposals objective, by defining goals of the project in a way that allows quantitative evaluation of a design with respect to each individual goal. A system that would look at each proposal and quickly use the expertise of the designer, which is built into it, to decide how it ranks with respect to others might save time and augment the accuracy and repeatability of evaluation. All aspects of the project that the designer deams important would be considered each time a proposal is evaluated. A design method that requires the designer to define all of the goals of the project would cause the designer to completely understand the problem. He/she would often learn or discover

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[1]Pugh, Stewart, "Concept Selection--A Method that Works", Proc. I.C.E.D. Rome (March 1981

[2]Houser, John & Clausing, Don "The House of Quality", Harvard Business Review Cambridge (May-June 1988

subtleties about the project that would otherwise go unnoticed. Such a method would also inspire different solutions while searching for all the possible configurations that need to be considered to define the goals.

1.2 The Spreadsheet Program

One possible solution to the problem posed above is to use an electronic spreadsheet program to define all of the goals of a problem in formulas. These formulas would be complex Boulean and algebraic expressions which evaluate how well a proposed solution achieves each goal. The completed spreadsheet would be influenced by all of the people working on the project. In this way it would incorporate all of the knowledge, expertise and expectations of everyone involved, not just that of the person doing the evaluation of the individual proposals. During evaluation, every aspect of the project that the group or individuals working on it thought was important would be considered. This would include the varied and possibly conflicting interests of marketing, engineering and manufacturing people. These interests would be expressed in terms that allow direct comparison, in spite of their differing nature.

The "Design Spreadsheet" would therefore be a type of expert system, in that it would contain all of the expertise gathered about a specific problem. It would provide a straight-forward method of evaluating designs that would minimize the effect of bias toward certain solutions over others, unless these prejudices are valid and intentionally built into the system.

In fact, the design spreadsheet would not take the creativity away from design. The person or group using the spreadsheet would have to think of all the possible solutions to a problem, while the spreadsheet would provide a ruler against which these solutions can be measured. The units of the ruler would be the extent to which the proposed design solves the problem. These units of measuring the success of a design would be defined by the users of the method. All of those issues that they decide are important would be included, while those that they do not care about would be left out.

This design method would allow the different objectives to affect the outcome according to their relative importance. Considerations that are very important such as providing the desired function might affect the score of a design more than things that may be less important such as the available colors of a design. Choosing the relative importance of all the relevent issues would be one of the main tasks of the group using this methodology. The relative importance would be represented by multiplicative weighting factors built into the spreadsheet.

1.3 The Damped Wrist Orthosis

To study this proposed design methodology, a design problem had to be posed. A good test case for this task is one that involves issues of engineering theory as well as more subjective issues such as aesthetic appearance. The subjective issues are the ones that seem to be more difficult for designers to quantify. It is important to have both types in a problem to test the spreadsheet's ability to compare inherently incomparable things on a single scale. Also, the problem should be simple enough to be able to come up with a first time spreadsheet in a realistic time frame yet complex enough to provide the trade offs that are essential to exhibiting the method's utility.

The problem chosen is the design of a damped wrist orthosis for people with tremor. Such a device would be worn by the user and would apply a resistive torque across the flexion/extension rotational axis of the wrist. The desired torque should be proportional to the angular velocity of the wrist in flexion and extension. See figure 1-0. The tremor present in the wrist in most multiple sclerosis people has a higher frequency than much of their intended motion. This allows the orthosis to act as a low pass filter. The lower frequency, intended wrist motion would be attenuated less than the higher frequency tremor.

It is estimated that about 700,000 people in the United States have intention tremor.[3] A device that eliminates or significantly reduces tremor would allow these people to perform such daily tasks as feeding themselves and writing as well as give them an increased level of independance in work activities. In addition to the basic functional issue of reducing the tremor, the intended device should be as attractive or at least as unobtrusive as possible. The user will be wearing the device in public and the better solution will appear as normal or natural as possible.

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[3]Adelstein, Bernard D, Peripheral Mechanical Loading and the Mechanism of Abnormal Intention Tremor, Thesis, M.S.M.E., M.I.T., Cambridge, MA 1981

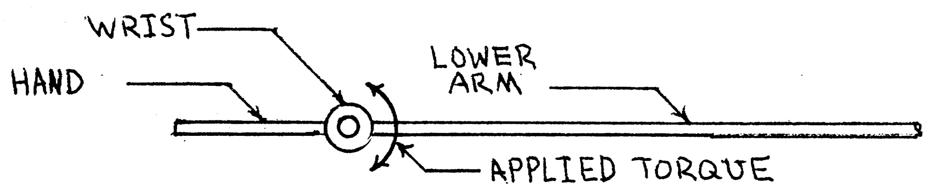

Figure 1-1: Schematic of hand, wrist and lower arm with desired damping torque

1.4 Outline of Work

This work was intended to study the benefits of using a design spreadsheet to evaluate and choose proposed solutions to a paticular problem. The spreadsheet to be developed is very specific to the problem. Special attention was given to keeping records of the spreadsheet development process and the proposal and evaluation process so that suggestions and recommendations for using this method can be made.

The first step was to define the design goals and decide what they depend on. This required thinking of all the things that can possibly affect the success of the damped wrist orthosis. A preliminary spreadsheet was then built around these goals. Then, reality testing the spreadsheet with extreme solutions with obvious goal scores was used to reveal flaws and necessary changes. Once the spreadsheet wass completed, it was used to evaluate different solutions, many of which were inspired by the process of writing the spreadsheet. Once a paticular design was chosen, the process was evaluated and recommendations could be made.

Chapter 2

The Design Spreadsheet

2.1 Structure of the Spreadsheet

As explained in the previous chapter, the design spreadsheet is used to organize the designer's opinions and knowledge about the paticular design project in a cohesive manner. This allows the effects of changes in a design or a completely different design to be studied without rethinking all of the logic involved in evaluating the success of a proposal. The designer's judgement and knowledge are represented in the spreadsheet as formulas that award scores to a design for the different goals and specifications of the project. The design being evaluated is represented by the values of the design parameters that are entered by the designer. The intended user is represented by the values of the user parameters which may or may not be changed by the designer. The designer's "judgement and knowledge" may very well represent the opinions and knowledge of many people whom the designer has consulted. The point is that all of this knowledge is collected and organized in a way that makes it simple and obligatory to consider every single aspect of the success of the project when making decisions. Whatever the designer or design team has decided is important to the project will be considered with every change or new proposal, not matter how insignificant it may seem.

The spreadsheet itself consists of four major parts, arranged in columns. Each major part is arranged to fill up one screen on the computer or one piece of paper so that the sections can be thought of as pages in the spreadsheet. The design goals with their scores, weighting factors and weighted scores appear in the first section. The next section contains the specifications, which are just intermediate calculations that the design goals refer to. The specifications represent issues too specific to be goals that cannot be parameters because they need to be calculated. The design parameters are in the third section. These are the parameters of each specific design that are evaluated and entered by the designer. There are four columns for the names of the parameters, their values, units and notes about the parameters and a column that displays an error message if a parameter or a specific combination of parameters is out of the defined as acceptable range. The fourth section contains the user parameters that give information specific to the user. These parameters may be needed for calculation of a specification or goal and can be changed to determine the performance of a design with different classes of users. The two parameter sections, design and user, contain variables whose values are entered by the designer. Both the specification and the design goal formulas refer to these sections. See figure 2-0 for a representation of a typical design spreadsheet.

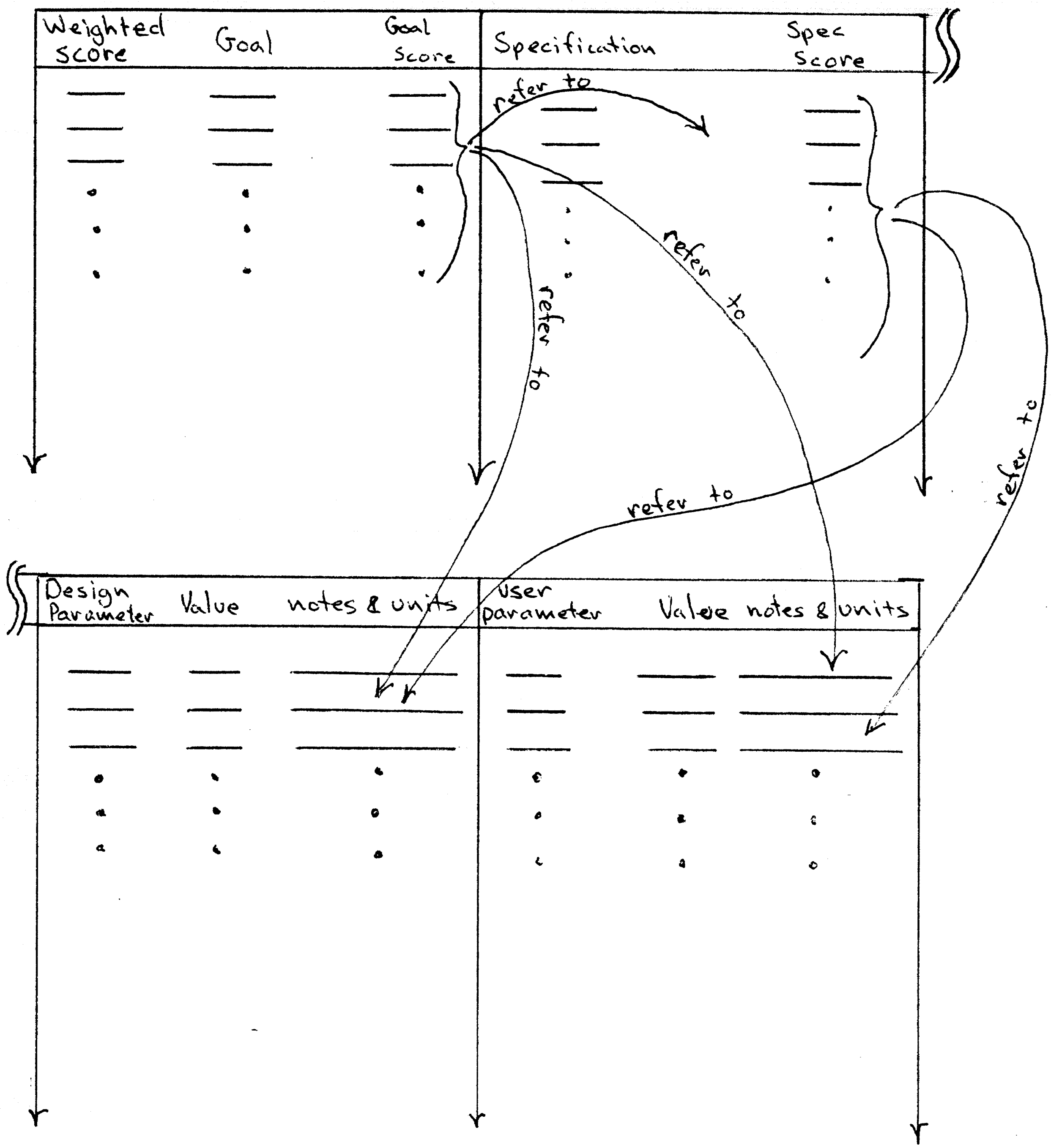

Figure 2-1: Typical spreadsheet set-up

Each proposed design receives an overall score that represents the sum of all the weighted design goal scores. A weighted design goal score is simply the goal score multiplied by its importance weight. The weights are normalized to put the overall score in a range that is easily understood, such as zero for the base line case, 100 for the best possible score and negative 100 for the worst acceptable case. See section for a complete description of the scoring process. The number that represents a design's overall score will tell the designer how that design rates with respect to the base line case as well as other designs being considered or already on the market. This score has no units and does not represent a physical quantity. It represents the expertise and opinion of the designer or design team and anyone who influenced them as well as the expectations and needs of the market that they have built into the spreadsheet.

Writing the spreadsheet requires a lot of thinking about what exactly is wanted out of the project and what exactly affects all of those goals and objectives. This is as important an aspect of the design spreadsheet as its more basic function of evaluating designs. Writing the formulas also helps inspire the designer to think of different approaches during the exhaustive search for all possible forms that a solution can take. The remainder of this chapter is devoted to explaining the spreadsheet that was written for the damped wrist orthosis design problem, in order to illustrate how the spreadsheet is used to evaluate designs. The following chapter discusses writing and using the spreadsheet as two integral parts of the design process, to show how a better understanding of the project is gained and the way that creativity is stimulated. For a complete representation of the spreadsheet as developed for the damped wrist orthosis, see Appendix .

2.2 Design Goals For the Damped Wrist Orthosis

The design goals are those attributes of a particular device that the designer wants to maximize. They represent functional consideraions that are in general not easily evaluated by objective engineering terms. In fact, many of the design goals are percieved as subjective issues that are difficult to quantify. For the damped wrist orthosis, the goals were especially difficult because a major aspect of the project is the cosmetic appearance of the orthosis. A good test of this design method is the comparison of these cosmetic goals to more straightforward ones such as tremor reduction and safety. To arrive at the goals, a lot of thinking, discussion and revision is necessary to make sure that everything has been considered.

The final list contains nine goals. Some of the awkward wording arises from the desirability of defining all the goals so that more is better. If low weight was a desired aspect of the design, there would be a goal "lightness" instead of "weight".

- Comfort: How comfortable the device is while being worn and used. This includes applied pressures related to the fit and use of the device as well as ventilation.
- Ease-use: Ease of use scores how easy the device is to use on a day to day basis. Donning and doffing, adjustments and any controls are considered.
- Economy: Economy indicates how well the cost of the device compares to a pre-determined estimate of what price the market will bear.

- Failureecon: How economical the device is to keep working. The cost of repairs and maintenance is compared with the estimated value of the function that the user gains from the device.
- Nonenvironcon: The extent to which the device does not conflict with the user's ability to interact with the environment. Included are snagging clothing, hair etc. and impairment of able-bodied functionality due to restraints the device imposes on the user with regard to the user's environment.
- Nonperscon: The extent to which the device does not conflict with the user's person or capability to move. The range of motion of the limbs involved and muscle fatigue are considered.
- Safety: How safe the device is with regard to minor injuries such as chafing or bruises, major injuries that cause reduced function over a finite length of time and catastrophic injuries that permanently reduce function.
- Tremor-reduce: The reduction of tremor attained while wearing the device. This is scaled by comparison to the user's tremor without aid as well as the nominal amount of tremor present in healthy persons.
- Unobtrusiveness: Measures how little the device is obtrusive in regard to visual appearance and auditory quality. Color, shape, bulk, surface finish and noise are considered.

The design goals are given relative weighting factors so that a change in one very important goal would have a greater effect than an equal change in a less important goal. The weighting factors chosen for these goals are tabulated below in table 2- along with brief descriptions of the reasons for such choices.

Table 2-I: Weighting factors for the design goals

Goal	Weight	Comments
unobtrusiveness	2	less important
comfort	3	daily use issue
nonenvironcon	3	daily use issue
tremor-reduce	10	purpose of design
safety	10	always important
economy	1	expensive concept
nonperscon	3	daily use issue
faileecon	1	expensive concept
ease-use	2	less important

2.3 The Designer's Expertise: Scoring the Design Goals

A paticular design is given a score for each design goal. These are determined from the user and design parameters which are entered into the spreadsheet by the designer. In this section, a general description of scoring is given, each design goal's dependency is outlined and examples of complete formulas are presented with thorough explanations. For a complete listing of all the formulas, refer to Appendix .

2.3.1 Description of Scoring System

The general system of scoring is presented here so that the next section, which describes the dependency of each goal, will be better understood. An example and explanation of an actual formula appear on page 32.

In order to translate the judgement of the designer into numbers that can be used to compare designs, simple formulas are used. All of the formulas in the spreadsheet appear in the specification or design goal columns, in the cells to the right of the word that represents that paticular specification or goal. The number that appears in the cell that contains a formula is the result of evaluating that formula in the context of all the design parameters, user parameters and specifications that appear in the formula. Most electronic spreadsheet software automatically evaluate the formulas everytime a change is made in the spreadsheet.

Each formula is built up from any number of terms that represent an individual idea and are scaled and normalized with respect to the base line case and maximum and minimum acceptable values. Keeping the formulas split up in this way allows for much quicker recognition of the components of a formula as well as easier editing. The basic principal is to take an engineering idea and abstract it into a number that has meaning only when compared to other pertinent values.

As an example, assume that for some goal to be maximized, the weight of a particular design must be minimized. A design parameter for weightis introduced so that the designer could enter into the spreadsheet the weight, in specifically stated units, of the design. The designer decides on a minimum value, a maximum value and a base line case at the time the spreadsheet is written. These do not change from design to design, unless the spreadsheet is being updated. The following term for weight would appear in the corresponding goal or as a specification that the goal refers to:

(@if(WEIGHT>BASELINECASE,
((BASELINECASE-WEIGHT)/(MAX-BASELINECASE)),
((WEIGHT-BASELINECASE)/BASELINCASE-MIN))

The @IF statement takes the value of the second argument if the first one is true, otherwise it takes the value of the third argument. The individual arguments are separated by commas within the second level of delimiters.

The base line case is the weight of the design that the designer is trying to improve upon. For the damped wrist orthosis, the base line case was chosen to be the unaided, tremor disabled limb. It is very important to be consistent with the choice of the base line case. Having made this decision, the designer must evaluate the base line case for every single parameter as the value pertinent to the chosen base line case. The resulting spreadsheet would give an overall score that is positive for a design that is better than the base line case, and negative for one that is worse. For the damped wrist orthosis, the base line case and the minimum acceptable value are both zero kilograms (since weight was defined as weight of the *device*) and the maximum acceptable value was chosen by deciding how heavy is too heavy.

The above general equation term will give a negative score if the design parameter is greater (or worse) than the base line case and a positive score if the design parameter is less (or better) than the base line case. The designer must define the parameters clearly so that the effect of the parameters is properly represented in the formulas, with regard to positive and negative scores. In either situation, the absolute value ranges between zero and one. This is the general form of a term in any of the specification or design goal formulas. If the parameter is a number chosen from a scale, the method is similar. Not every term will have a positive and a negative possibility. Sometimes the base line case will be the maximum or minimum acceptable, in which case only one part of the above term will be necessary. Also, there may be some absolute cases such as "if the design is flourescent green, unobtrusiveness gets a negative ten". Whatever is needed can be built in, using the above form as a basic building block.

To scale the scores, a consistent system must be chosen. For the design spreadsheet developed here, the scale ranges from -10 to +10 for the design goal scores. For simplicity, any intermediate calculation that appears in the specification column (as the above example would) is scaled from -1 to 1, except when the number is better understood in common engineering units such as degrees celcius and gets scaled properly in the actual goal score.

2.3.2 Design goal logic

The goal score formulas are written in terms of specifications and the design and user parameters. An explanation of the logic behind each goal score is presented here along with the formulas for each goal. See appendix for these formulas and the specification formulas. Things are described down to the level of the individual parameters, so that the actual formulas can be understood from reading this explanation. Many parameter, specification and goal names have been contracted due to the limited formula length in the spreadsheet software.

Comfort

(((FIT*3.4)+(COOLNESS*3.3)+(((@MIN (1,SHEARLVL))*-1)*3.3))

The score for comfort is determined by the specifications fit, coolness and shearlvl. fit is composed of two components, the pressure that is applied to the limb to hold the orthosis in place (design parameter clamppress and the pressure applied to the limb that results from reaction to the damping force used to attenuate the tremor). The clamping pressure is compared to a maximum acceptable pressure, with the base line case being zero. The pressure applied to the limb during use is calculated from the area of application and the length of the moment arm. This pressure results from extension motion and flexion motion and thus is represented by the two specifications exnonpress and flnonpress, which mean "non pressure in extension/flexion". These specifications are calculated from many design parameters that represent the moment arms and area of applications for all the different ways that pressure is applied.

Coolness is calculated from the ratio of the skin temperature rise under the orthotic material to the maximum acceptable skin temperature and the amount of skin covered. The skin temperature under the orthotic material is estimated with a simple model that uses the thermal conductivity of skin and the splint material. Shearlvl represents the shear pressure applied to the skin during flexion/extension of the wrist and is calculated from the user parameters flexion and extension which are the maximum producable flexion and extension torques at the wrist, and the design parameter sknshear which is the ratio of torque applied at the wrist to shear force transmitted to the user's skin.

Ease-Use

((5*ADJUSTMENTS/5)+(5*PUTON/5)) The goal ease-use depends on the two design parameters adjustments and puton. The number and complexity of any adjustments to the device during use and the difficulty in donning and doffing it are both determined by these unitless parameters with well defined ranges that assign particular numbers to the parameter for specific cases (see appendix for the use of these scales in the units and notes column). The designer can easily decide which number to assign these parameters by comparing the requirements of the design to explanations given in the design parameter column.

Economy

(@IF((MAXCOST=0),0,(((MAXCOST/2)-COST)/(MAXCOST/2))*10))) Economy is determined by two design parameters, cost and maxcost. It is not necessarily true that the least expenxive device is the most economical. A device that works better and seems or is more complex will often cost more but seem just as economical. Therefore, this goal compares the actual selling price of the device to a maximum cost that could be charged for such a device, determined from products of similar complexity already on the market. Note that this formula compells the designer to do some cost estimation and make marketing and profit decisions.

Failure-econ

(@IF(COSTFIX=0),0,(@IF((TREMRATIO=0), -10,(@MAX(-10,((-10/0.2)*(COSTFIX. (TREMTRATIO*LOSS*RELYDAYS))))))))) To determine the score of failure-econ, the cost to keep the device in working order is normalized by the estimated value of the returned function. The economy of failures and maintanence can then be seen in relation to what the device actually gives back to the user. The cost to keep the design in working order is determined by the design parameter costfix and the specification relydays. The cost to fix an average breakdown is estimated by the designer, while the mean time between failures, or days of reliable operation is calculated from the 50% design life, in cycles and the user parameter cycles, the estimated cycles per day. The value of returned function comes from the user parameter loss, the estimated dollar value of the lost function per year due to tremor and the specification tremratio which calculates the ratio of the damped tremor to the unaided tremor. Assuming that the loss function is linearly related to the amount of tremor, the dollar value of gained function can be estimated from this information.

Nonenvironcon

((SNAGLESSNESS/5*3)+(FUNCTIONALITY*7)) Nonenvironcon uses the design parameter snaglessness and the specification functionality. Snaglessness is a unitless parameter that defines the extent to which the device will not snag clothing, hair or other parts of its environment. Functionality represents the ability of the user to perform normal functions while wearing the device. It refers to the design parameter accdiam and the user parameter uaccdiam which are the diameter of the smallest hole that can be accessed with the hand while wearing and not wearing the device, respectively. functionality also looks at the design parameters palmdist, writedist and contrestrict. The first two represent how well the hand can interact with objects and surfaces. Palmdist is the distance of the actual hand from a flat surface while the hand and orthosis are resting on the surface. Writedist is the distance of the lower side of the hand from a flat surface while the hand and orthosis are resting in a writing position. contrestrict is the percentage of the surface of the hand and arm that can not be used as a contact surface. Such issues as delicate parts, button or switches, straps etc. on the surface of the device will reduce tha ability to push on objects or just use the limb in general. The score of the specification fngrfrdm also affects functionality. Finger freedom represents the ability to use the hand to manipulate objectswhile wearing the device. Fngrfrdm's score is partially determined from the design parameters index, middle and forefinger which indicate wether or not these fingers can touch the thumb. Area which is the percentage of reduced area in the circle formed between the thumb and forefinger when they are touched and folding which is the percent reduction of the ability of the thumb to be folded towards the palm also affect fngrfrdm.

Nonperscon

((R.O.M.*3.3)+(PURPATTEN*3.3)+(NONFATIGUE*3.4))

Nonperscon is calculated from the specifications r.o.m., purpatten and nonfatique. R.O.M. represents the range of motion retained by the user while wearing the device. It consists of the design parameters flexion, pronation and abduction which represent the ranges of motion comfortably allowed by the device for wrist flexion/extension, lower arm pronation/supination and wrist abduction/adduction, respectively. Purpatten is the extent to which the device does not attenuate purposeful motion. It is calculated from the design parameter damping which is the damping constant applied across the wrist and the user parameters extorque and fltorque which are the maximum wrist extension and flexion torques that can be produced at the wrist. Nonfatigue represents how little the device fatigues the user's muscles during normal activity. It is calculated from the design parameters weight and damping, the specifications wcforce and wctorque and the user parameters uarmlength, opforce and tremfreq. There are two types of fatigue involved, upper arm and shoulder fatigue due to supporting the weight of the device, and fatigue of the forearm muscles that extend and flex the wrist due to the damping force. Each of the fatigue terms reduce the score as the muscles approach the worst acceptable force. In the first type of fatigue, scores are calculated for holding the arm outstretched. Opforce is the normal operating force of the arm, or the force required to lift the arm. Wcforce is the worst acceptable amount of force. This represents the force that is half way between the operating force and the user parameter maxforce, the maximum force that can be sustained for one minute. This was chosen instead of the maximum force because fatigue would arise at much lower forces than the maximum. Whole arm fatigue is calculated from the weight, the operating force, the length of the arm and the worst case force. Fatigue at the wrist uses wctorque, which is similar to the worst case force. It is the torque half way between tremtorque, the torque that produces the tremor (a specification), and the lesser of extorque and fltorque, which are the maximum torques that the user can produce in extension and flexion. Damping, the damping constant and the user's tremor frequency are used to compare the damping torque to the worst case torque for wrist fatigue.

Safety

(((PROBMININJ*-1)*3.3)+((PROBCATINJ*-1)
3.3)+((PROBMAJINJ-1)*3.4)) The design goal safety is calculated from probabilities of safe operation whith respect to three different types of injuries. A minor injury is one that can be attended to by the user and causes reduced function only for the length of time required to attend to the injury (such as chaffing or scratches). Major injuries are

ones that require a proffessional to attend to and cause reduced function for a period of time longer than that required to attend to the injury. A catastrophic injury is one that causes permanently reduced function. The design parameters in the safety formula are probmininj, probmajinj and probcatinj. These parameters are estimated by the designer.

Tremor-reduce

@IF(DAMPTREM=TREMAMP,0,(@IF(DAMPTREM <=0.01,10,(TREMRATIO*10)))) Tremor-reduce, being the amount that the device reduces the user's tremor is the only goal score likely to show an improvement over the unaided, tremor inflicted limb. It is calculated from the specifications damptrem, the predicted tremor amplitude while wearing the device, and tremratio, the ratio of the predicted damped tremor to the tremor present in the user without the device. Damptrem is calculated from the design parameters damping, the damping constant of the device and minertia, the moment of inertia that the device adds to the hand as well as the user parameters handinert, tremfreq and tremamp which are the moment of inertia of the hand, the frequency of the tremor and its amplitude, respectively. A second order mass, spring and dashpot system is used as a simple model. The moment of inertia and the tremor frequency are know, so the muscle torque can be estimated. With this and the damping constant, the damped tremor can be caclulated. Tremratio comes from the calculated tremor amplitude while wearing the device, damptrem and the user parameter tremamp.

Unobtrusiveness

(((COLORMATCH)*2)+((SHAPENTRLNSS)*2)+(NOISE*2)+(UNBULKY*2)+((FINISH/4)*2)) The goal unobtrusiveness tries to take very subjective aesthetic qualities and evaluate them in an objective way. It is calculated from the specifications colormatch, shapentrlnss, noise and unbulky and the design parameter finish. Colormatch represents how well the device matches the user's skin color. It is calculated from the design parameter devicecolor and the user parameter skincolor which give the color of the skin and user on a comparative scale that the formula for colormatch understands. Shapentrlnss quantifies how natural the device appears. It looks at the design parameters seams, protusion, #protusion and continuity. Seams and continuity are yes or no questions that tell if the device has seams and if it has a continuous surface without holes or lots of breaks. Protusion is the average distance from some mean radius of the protusions while #protusions is the number of such protusions. Noise represents the extent to which any noise produced by the device is not annoying. It relies on the design parameters noiselvl, frequency, noisecntny, freqfluc and lvlfluc which represent the level, frequency and continuity of the noise as well as wether or not the level and frequency flucuate. Unbulky represents how small the device is. It is a function of the design parameters handsize, armsize, wristsize and armlength and the user parameter sleevetype. The design parameters tell how far the device sticks out from the various parts of the limb being considered as well as the length of the lower arm covered by the device. Sleevtype simply indicates if the user wears long sleeves or not.

If the user does wear long sleeves, as long as the sleeve fits over the device, armsize and armlength have no affect. Finish is a simple scale that indicates how much of the surface of the device has a soft, matte finish.

2.3.3 Some Formulas Explained

To demonstrate how the above logic is built up to form an entire formula, some actual formulas from the completed spreadsheet are presented and explained in detail below.

The design goal unobtrusiveness is a typical example of a consideration that is inherently subjective but must be expressed in terms of parameters that can be evaluated by the designer consistently for each design without favoring something that is not explicity scored by the formulas. As described before, unobtrusiveness has five terms in it. Four of them come from the specification column, and are therefore already scaled between negative one and one. The fifth, finish needed no intermediate calculations and thus comes directly from the design parameter column. It can take on a value from zero to negative four and is therefore divided by four to scale it between zero and negative one. In the formula for unobtrusiveness, below, note that each term is multiplied by two. This is done to put the five terms together on a scale that ranges from negative ten to ten (assuming that each of the five terms ranges from negative one to one). These numbers are all two here because the five terms carry equal importance. If one term was more important than the rest, the distribution would be different.

((COLORMATCH*2)+(SHAPENTRLNSS*2)

+(NOISE*2)+(UNBULKY*2)+((FINISH/4)*2))

The four specification terms in the goal for unobtrusiveness have formulas of their own in the specification column that return values between zero and negative one. If it was possible for a design to improve upon the base line case with respect to any of these, then the score for that specification would also be able to go to positive one. In the case of unobtrusiveness, the effects are all degradations from the base line case, and therefore are zero or negative. It is important, however, to note the possibility of positive and negative scores in a formula and consider the full range of values possible when scaling the formula.

Colormatch is a specification that compares the color of the device to that of the user's skin. If the designer has assigned the value of zero to devicecolor, this means that the device has an unnatural, bright primary color, and the value returned for colormatch is negative one. Otherwise, colormatch compares the color of the user's skin, skincolor to devicecolor and returns a score between zero and negative one based on the difference between the two:

@IF(DEVICECOLOR=0,-1,@IF(DEVICECOLOR=SKINCOLOR,0,
(((@ABS(DEVICECOLOR-SKINCOLOR))/4)*-1)))

Shapentrlnss is a specification meant to quantify the degree to which the shape of the device is natural looking. It is composed of six terms, each of which range between zero and one. Since these terms are already normalized, they were simply added and the sum divided by negative six (the negative sign is necessary because the effect of each term is negative, but has positive value):

((SEAMS+((PROTRUSION*#PROTRUSION)/20)+CONTINUITY+
RADII+GEOCEN+LTOD)/-6)

Seams is a design parameter which has a value of zero if there are no visible seams and one if there are. Protrusion is the average distance (in centimeters) of protrusions from a mean (or typical) diameter of the device and #protrusion is the number of protrusions in the average. The maximum product of these two parameters is 20 due to the maximum values set for each of them, so the product is normalized by this value. Continuity is another yes/no question that indicates wether or not the surface of the device is continuous with respect to holes, texture etc. The last three terms are themselves specifications. Radii evaluates the average radii of curvature of the hand and the device in planes oriented along the limb and across it. The formula first calculates percentage differences amongst these and then averages these differences to get a final specification score for radii. Geocen and ltod are calculated similary. Geocen deals with the location of the geometric center of the device and the hand, while ltod compares the length to diameter ratios of the device and limb at different parts of the limb. See appendix to completely trace the logic of these and any other formulas.

Chapter 3

The Design Process

3.1 Introduction

Traditionally, the design process involves the creative activity of drawing on one's past experience for possible solutions and theoretically or experimentaly testing that pool of proposed designs. When all of the possibilities have been evaluated, the best ones are chosen, possibly combined and the process starts over with all of the subsystems, sometimes called detailed design. One important part left out of this description is defining the problem. The engineer or design team is given the assignment of designing a product to fill a certain niche in the market, or compete with existing products on the market. This does not specify exactly what is wanted out of the project in terms that the engineer can discuss objectively. Therefore, a major part of the design process is defining the problem in terms that the engineer can use to evaluate proposed designs in a consistent manner.

The design spreadsheet, as a method or process for design, is useful in all three parts of the design process mentioned above. Defining the objectives of a project is done in writing the spreadsheet. Choosing amongst different proposals or different subsystems of a design is accomplished by using the spreadsheet. The creative activity of actually thinking of the different possible solutions is still, as always, carried out by the individual designer or design team as a singular thought process. The nice thing about the design spreadsheet is that using and writing it often causes the designer to think of new solutions and combinations. The design spreadsheet is a tool that augments the creativity of the designer, something that any designer is always trying to do.

This chapter explains how the spreadsheet was used in the damped wrist orthosis project as part of all apects of design. Attention is given to the *process*, the actual reworking and thinking activities that are important to understanding the problem being solved and inspiring the imagination.

3.2 Developing the spreadsheet

3.2.1 Choosing the design goals

The first step in writing the design spreadsheet is to choose those characteristics of the product that will be the design goals. These are general attributes of the design that will be calculated from the individual pararmeters and specifications of the design. As an example, the amount of raw material used in the product would probably not be a goal, but this parameter could affect actual goals such as economy or unbulkiness which could very well be goals.

When choosing design goals, the designer will discover right away that he/she has to decide at what level the goals will be. It is possible to have just one goal goodnessofdesign or hundreds of goals that each represent a very particular aspect of the problem. A balance needs to be found between having too many goals which confuse the results and too few goals that keep the designer from distinguishing between opposing effects.

A good starting place is to look at trade offs. A typical trade off found in designing is the one between economy and durability. A strong, very durable device is usually more expensive. Putting the effects of economy and durability in one goal would mask this trade off because the designer would not immediately see, for example that a choice had done well in economy but poorly in durability. If the designer tries to think in terms of basic issues, the design goals will be fairly easy to choose. It is important to remember that new goals may become apparent at any time during the process of writing the spreadsheet. There must be enough openness in the attitude towards the spreadsheet for these items to be added as goals, if necessary, or included in the formulas for other goals.

For the spreadsheet at hand, the final goals are listed on page 18. These goals were decided upon by continually updating the list during the process of writing the formulas for them. It is interesting to look at the development of this list.

The very first list of goals that was developed enough to be entered in a notebook is:

- COSMESIS
- TREMOR REDUCTION
- NON-INTERFERENCE
- MANUFACTURABILITY
- COMFORT
- SAFETY

Very soon after this list was made, cost was added. In hindsight, one can see an obvious relationship between manufacturability and cost. In the final choice of a design, the important issue is really economy, which will more than likely involve cost and manufacturing issues.

While formulas, specifications and parameters were being composed for these goals, continual changes in this list were made. Unobtrusiveness was taken from the specification column and made a goal, replacing cosmesis because items like the noise that the device made are better represented by unobtrusiveness. Thought experiments about how the device would be used on a day to day basis inspired reliability and ease of use to be added to the design goal list. The specification range of motion was moved to the goal list because it was soon realized that the orthosis would probably restrict the user's range of motion. It later became part of non-interference which was subdivided into the two goals: nonenvironcon and nonperscon. Reliability was eventually replaced with failure-econ to incorporate not just how reliable the device is but how much functional value (in dollars) is lost when it is unavailable.

This goal development process took place during most of the formula writing stage. The importance of iterations and continual updating is stressed here. If a list is chosen and stuck to, most of the learning that can be achieved during the writing stage will be severely inhibited.

Once the design goals were finalized and most of the formulas completed, the weighting factors of the design goals had to be chosen. The first approach was to rate the goals in order of importance and give them weights from one to nine according to that order. This was done by looking at the goals two at a time and choosing the more important one. Once each goal had been compared to all the others, a ranking of importance could be made. The problem with this method is that the most important goal is ten times as important as the least important goal, which may not be accurate. Later, while using the spreadsheet, the weighting factors were changed to reflect groupings of goals with similar importance. The final choices appear in Table 2-.

3.2.2 Writing the spreadsheet as part of designing

In the previous section, the development of the design goals was laid out to emphasize the thinking process that goes on when writing the spreadsheet formulas. Here, it is stressed that this process is a very important part of design.

Many important aspects of the project were learned during the writing stage. The relationship between the cost of maintenance and the value of the returned function was developed while simply trying to define the goal for reliability. It was soon discovered that it did not matter how little it would cost the user to keep the orthosis in working order if the user did not get anything in return from it. Likewise, the more the person gained from wearing the device, the more that person would be willing to spend to keep it running.

Other trade offs that were more or less obvious became apparent when trying to come up with concrete, objective ways of evaluating specific issues. At first glance, one would think that less skin coverage is better because there would be better ventilation. When the pressure applied to the skin due to damping forces is considered, however, you realize that more area can be better. The well known trade off between strength and economy was discovered to have more to it. A heavier, stronger device will score worse on natural appearance, fatigue and overall bulk. The relatively simple issue of the amount of damping to apply is seen to involve more than just the balance between purposeful motion attenuation and tremor reduction. There is also the issue of fatigue. When trying to define fatigue, it was obvious that a greater damping constant will fatigue the wrist sooner.

Some of the trade offs mentioned above are obvious, and some are not. If an engineer was designing in the traditional manner, he/she would be evaluating designs based on what was thought to be important to the project. Many of the issues accounted for in the spreadsheet would simply never be considered because there was no system for bringing these issues into the designer's conscious thoughts. Even if most of these issues were thought of, it would be impossible to account for them all for each proposed design. When writing the formulas for the design goals, the designer tries to think of every thing that will affect how well the goals are met. Each goal is considered individually, one at a time, making it much more likely that every effect will be thought of.

Writing the spreadsheet is, therefore, very much part of the design process. It is not simply an organizational chore that must be done before the real work can be started. If this first stage in designing is undertaken with an openness to creativity and all types of ideas, feasable or not, many possibilities will surface that will have a great affect on the outcome of the project.

3.3 Making choices: using the design spreadsheet

3.3.1 Reality testing

Once the spreadsheet is thought to be complete (because it never really is), the designer begins testing it with extreme case designs that should give obvious results for the goal scores. The intent here is to do things that should give a certain result, and see if that is true. If the results are as expected, then the spreadsheet is ready to test the real proposals. If the results are non-intuitive, then the spreadsheet has either demonstrated an effect that was not thought of or has been forgotten or the spreadsheet needs revision.

In the wrist orthosis example, three obvious solutions were tested. The values for the base line case were entered to see if goal scores of zero would be obtained. It is important to enter these parameters blindly, without trying to bias them to get a score of zero. A design that involved simply strapping the hand to the arm of a chair was tried and then strapping the arm to a board.

The base line case revealed a lot of errors in the formulas. Simple problems such as values being out of range, unanticipated combinations of numbers and dividing by zero had to be fixed. The other two solutions gave results that were expected. Strapping the arm to a board gave a better score than strapping it to a chair because the user still retained gross arm motions. The only surprise was that these scores came out negative, or worse than the base line case, the unaided limb. This was disturbing because it was originally thought that reducing tremor would outweigh the other issues.

3.3.2 Correcting the spreadsheet

After testing the spreadsheet with these obvious examples, it was decided that some revision of the weighting factors was necessary. Due to the way the formulas were written, some of the goals recieved extremely negative scores. In the case of unobtrusiveness, everything that is added to the hand is obtrusive. The formula considers many different forms of obtrusiveness, and thus becomes very negative very fast. In comparison to other designs, unobtrusiveness really shouldn't get such a bad score, so its weight was changed. The goal of economy was scored between zero and negative ten. Negative ten was assigned to the design that cost 90% of the maximum amount that could be reasonably charged for a device of similar complexity and returned function. Zero was assigned to the device that was free. This type of formula was also giving very negative scores since most designs are going to cost near the maximum. The range was changed to go from 50% to 90% of the maximum.

In this manner, all of the goals were adjusted to give intuitively correct results for the test cases. After all, the goal scores are supposed to represent the opinion and expertise of the designer. It is important to remember, however, that one should not simply adjust the formulas to favor paticular designs but rather to reflect the more abstract objectives.

3.3.3 Entering proposed designs

Once the spreadsheet was revised with working formulas and the corrected weighting factors, actual proposed designs were entered into the design parameter column. During the process of writing the spreadsheet, a lot of insight into what is good and what is not was gained, so that some very good solutions had emerged in the mind and notebook of the designer.

Three designs were tried in the spreadsheet. The type of cuff, the type of damper and the way that the damping load was transmitted was varied in the designs. In the next chapter, these three designs are presented with their results. In the conclusions chapter, there is a discussion of what was learned from this example, where the spreadsheet succeeded and where it fell short.

Chapter 4

The proposed designs

4.1 Description of proposed designs

The three designs that were chosen to be entered in the spreadsheet are presented in this section. These designs do not necessarily represent every possible solution, but they are the ideas that emerged out of the process of writing the spreadsheet and thinking about the orthosis over the months of spreadsheet editing.

The first design is sketched in figure 4-1. It consists of two cuffs hinged at the wrist. The cuffs are made out of orthoplast, a product that is normally rigid but becomes pliable when submerged in hot water. For a final design, the orthoplast would probably be replaced with some more permanent material. The hand cuff wraps around the hand leaving two holes, one for all four fingers and one for the thumb. The lower arm cuff is split on the underside of the arm. Both cuffs are fastened with velcro straps. The hinge uses a steel plain bearing that is press fit into the cuff material and crimped in place like a rivet.

The damping force is applied by a linear viscous damper. The damping constant may be adjusted for the user by changing the size of the orafice in the piston. The damper is mounted on top of the arm and translates the damping force across the wrist via a four bar linkage composed of two bars, the hand cuff and the arm cuff. A bearing mounted axially with the damper transmits the longitudinal loads to the lower arm cuff. In this design, as with the others the problem of the changing axis of rotation of the wrist is dealt with in the play between the person's skin and the cuff material.

The second design uses the same linear viscous damper but has a different cuff system and load transmission. See figure 4-2. In this solution, the damper is mounted on the side and the damping force is transmitted via a rack and pinion. The pinion is located at the rotation axis and is grounded to the rotation of the hand cuff. The lower arm portion of the device has four padded areas of contact with the arm. This idea developed from a combination of exercise equipment and studying the way that damping loads are transmitted to the skin. With the four pads, it is clear where the force couples are applied to produce the torque about the wrist. In further development, this design would allow the designer to use the spreadsheet to balance the trade off between coolness and the pressure applied to the skin by adjusting the size of the padded contacts.

The third proposed design uses the same cuff system as the first design, but has a magnetic particle brake attached at the wrist rotation axis that simulates a viscous damper. The magnetic particle brake would require battery power and some simple control to simulate the desired damping profile. These circuits could be mounted on the user's arm or wheelchair. See figure 4-3.

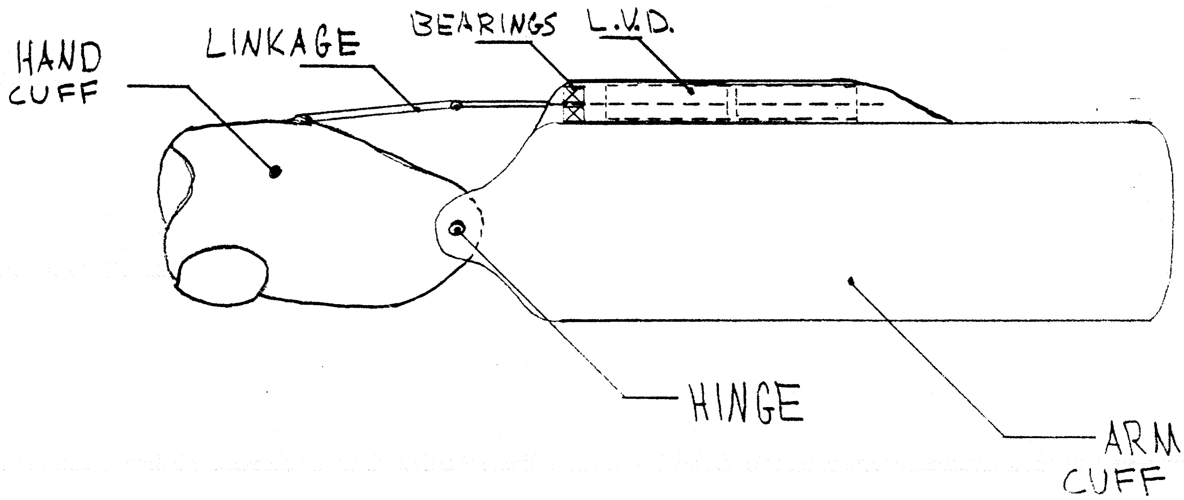

Figure 4-1: Proposed design #1: hinged orthoplast cuff with linear viscous damper and four bar linkage.

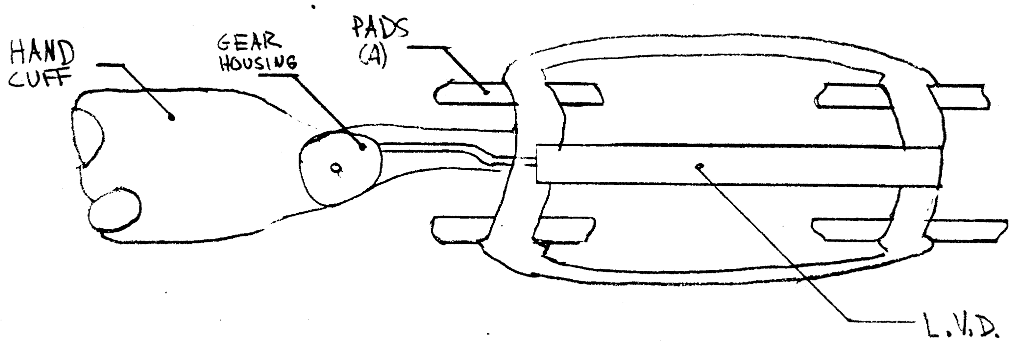

Figure 4-2: Proposed design #2: hinged aluminum and orthoplast cuff system with linear viscous damper and rack and pinion transmission of damping force.

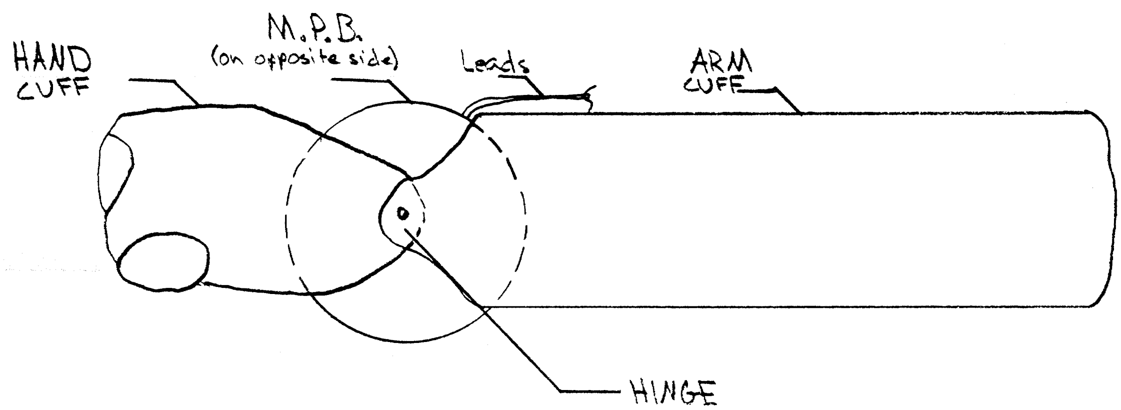

Figure 4-3: Proposed design #3: hinged orthoplast cuff with magnetic particle brake applying damping load directly to the wrist axis.

4.2 Results from the spreadsheet

The three designs' parameter values were entered into the spreadsheet to decide which would be best. Since this exercise is a test of this particular design process, the proposed designs were straightforward enough that we had some expectations as to how goal scores would turn out. Tables 4-I through 4-III show the design goal scores and the final scores of the three designs. See appendix for a complete printout of the spreadsheet with the apporpriate parameters for each design.

Most of the results were not at all surprising, and the reasons for this are discussed in the next chapter. The second design scored the best, while the third design had the lowest overall score. Many factors affected these scores. The magnetic particle break is bulky, the batteries require maintenance and take up space but there is nothing attached to the lower arm which is good for unobtrusiveness. The third design did do well in safety because there is less mechanism to break and cause injury. The rack and pinion system of the second designdid well because it can be covered and therefore is less likely to snag or be dangerous, it is less flexible and takes up less space. Also, the cuff system used in the second design covers less skin and is more natural looking due to the possibility of having the parts mimick natural shapes in contour, radii of curvature and length to diameter ratios. If the first design had done well with respect to its linkage, it would be interesting to try the cuff system of the second design with that linkage.

From this exercise, the second design would be chosen for detailed design. The spreadsheet could be used to help decide between trade offs in detailed design. The more in depth and detailed the spreadsheet is, the more it can help in this stage of design.

Table 4-I: The design goal scores and total score for design #1

	Weighted Score	Importance Weight	"GOAL"	Goal Score
			note	
1	-5.05	2.00	unobtrusiveness	-2.53
2	-20.81	3.00	comfort	-6.94
3	-12.05	3.00	nonenvironcon	-4.02
4	72.94	10.00	tremor-reduce	7.29
5	-2.32	10.00	safety	-0.23
6	0.00	1.00	economy	0.00
7	-11.40	3.00	nonpersoon	-3.80
8	-0.00	1.00	failureecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 10.21

Table 4-II: The design goal scores and total score for design #2

	Weighted Score	Importance Weight	"GOAL" note	Goal Score
1	-3.45	2.00	unobtrusiveness	-1.73
2	-20.22	3.00	comfort	-6.74
3	-6.23	3.00	nonenvironcon	-2.08
4	72.94	10.00	tremor-reduce	7.29
5	-1.99	10.00	safety	-0.20
6	0.00	1.00	economy	0.00
7	-11.38	3.00	nonperscon	-3.79
8	-0.00	1.00	failureecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 15.78

Table 4-III: The design goal scores and total score for design #3

	Weighted Score	Importance Weight	"GOAL"	Goal Score
			note	
1	-4.83	2.00	unobtrusiveness	-2.41
2	-22.20	3.00	comfort	-7.40
3	-6.23	3.00	nonenvironcon	-2.08
4	72.94	10.00	tremor-reduce	7.29
5	-1.99	10.00	safety	-0.20
6	0.00	1.00	economy	0.00
7	-11.46	3.00	nonperscon	-3.82
8	-0.00	1.00	failureecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 13.49

Chapter 5

Conclusion

5.1 Overview

In mechanical design, the designer is confronted with the task of balancing organizational, creative and analytical tasks. He/She must completely understand the project at hand, that is, a complete definition of the project must evolve before proposing of specific designs can begin. This definition will usually result in a list of criteria or goals that the final design should fulfill. Organizing all of these desires can be very tedious if it is a complicated design task. The creative part of designing requires the designer to think of possible solutions utilizing past experience and new combinations of subsets of solutions retained in the designer's memory. Evaluating how well proposed designs meet the criteria requires analyzing the design in terms of function, appearance and whatever else is pertinent to the project.

The design spreadsheet is a tool or method of design that facilitates all of the above steps in designing. Writing the spreadsheet causes the designer to define the project in more detail than would ever be done by conventional methods. The designer is forced to express every aspect of the project in terms that can be evaluated objectively.

The creative aspect of designing is not done by the spreadsheet, but a lot of insight into the problem comes out of the spreadsheet. When writing the spreadsheet, the designer will have to think of the possible classes of solutions in order to come up with reasonable formulas for the goals and specifications. This causes the designer to think of a large number of possible solutions for an individual aspect of the design, without considering how they would relate to other parts or aspects of the final product. When the designer sits down to make sketches and think about possible solutions, a lot of things will already be suggested from the previous activity of writing the spreadsheet. Furthermore, when he/she evaluates the individual designs, the results will prompt combinations that may not have ever been noticed. Looking at individual scores throughout the spreadsheet will help decide what should stay and what should be combined with other designs.

The analytical part of designing is the main purpose of the spreadsheet. Just evaluating the parameters and entering their values will result in an indication of how good the design is. Often, evaluating certain parameters will require calculations that would be done in more traditional design situations to test the validity of a solution. Here, these results would be seen in a more comparative light, giving the designer some objective basis to make decisions on.

This project was done to evaluate the use of the design spreadsheet. As mentioned before, the investigation was carried out as a case study. A design spreadsheet was written for the design of a damped wrist orthosis. The orthosis would be worn by persons with intention tremor in the flexion/extension motion of the wrist. The next section presents the findings of this study.

5.2 Discoveries and recommendations

The results of this study were pretty much as expected. The design spreadsheet seems to be a very good method for organizing the design process. Most of the statements made about the spreadsheet throughout this document are a result of using it and therfore represent the conclusions of the study. The spreadsheet was found to be most useful in organizing the definition of the project and learning exactly what factors affect the success of the product.

A number of things were learned about the spreadsheet that would be useful for someone to know before trying to design with this method. They are listed as follows:

- A large part of the spreadsheet's usefulness is in *defining* the project, forcing the designer to find *objective* ways of defining and measuring the success of a particular design.
- The spreadsheet works best for a project meant to perform a number of functions successfully. The wrist orthosis was meant to do only one thing, reduce tremor, and therefore some of the decisions were obvious. If a project has ten functions, it is much easier to see how the spreadsheet will help.
- Making the spreadsheet inspires the creative design process by causing the designer to think, abstractly, of all the forms that a design can take.
- When using the spreadsheet, if each goal and/or specification is looked at individually, the designer can find new solutions that take the best of a number of different solutions.
- If the spreadsheet is well written, it can reveal flaws and gaps in the designer's understanding of what may be better or worse. It can point to areas where additional expertise or data is needed.
- The spreadsheet forces the designer to decide what goals,

specifications and terms in the equations are more or less important, causing a greater conscious understanding of the problem.

- The level of complexity should be well thought out. The more detailed the spreadsheet, the more it can help the design process. There must be a balance between time spent and the amount of help received.

Some of the above statements need explaining. The issue of the number of functions that a proposed product will have is important to the satisfaction that will come from using the spreadsheet. The damped wrist orthosis does not really use the spreadsheet very well. It is a good problem to exhibit the difficulty and necessity of defining a lot of subjective issues in objective terms, but it does not have a great balance between functions. A better project for further study of this method would be one that had the possibility of providing a number of functions, but each of which were coupled to the appearance or marketability of the product. A situation such as this would create a complicated set of formulas that would be an ideal application for the design spreadsheet.

The issue of the spreadsheet teaching the designer something he/she may have not already realized is interesting. Since the designer creates all of the formulas and customizes all of the rationale in the spreadsheet, it might seem impossible to learn anything from it. But there may be certain affects that would not be otherwise noticed by the designer. Every time the spreadsheet gives a surprising result, such as scoring one proposal better than one that was expected to excel, the designer should find out why, and may decide to incorporate some new logic into the spreadsheet or simply fix something that is wrong. The emphasis on the usefulness of the spreadsheet is that the designer can not be expected to remember everything about the project. There may even be things that are kept in the subconscious mind until they are coaxed out. This is where the spreadsheet helps. It keeps track of everything and therefore will account for effects that may not be noticed each time a proposal is looked at by the designer. In the damped wrist orthosis example, many of the designs were getting negative scores. This was confusing until it was realized that the nature of the product is such that it degrades the performance of the unaided hand in all ways except one--the reduction of tremor. This realization required rethinking of the weighting factors because a good design just shouldn't come out negative because it does not look and feel like a real hand.

A drawback in the spreadsheet developed for this study is that it stops at a certain level of complexity. While it breaks down all the cosmetic, comfort and other human-factors related issues, it never goes into detail about the way that the damping force is obtained. It was not realized until late in the project that more in depth formulas would greatly help in detailed design, which really could not be done with the help of the spreadsheet as it stands.

This brings up a complicated issue in the use of the spreadsheet. In order to write meaningful formulas for the specifications and goals, the designer has to understand what form the solutions will take. He/she has to know that the skin is going to be covered in order to estimate how this will affect skin temperature. In order to do this, it is sometimes necessary to back up a level and ask the designer for the final result as a parameter that would otherwise be a goal or specification. In the oal formula of safety, for example, there are probabilities of injury. It may have been more revealing to ask how many injury or failure modes are there, how do they take place, etc. and essentially have the spreadsheet go through the calculations that the designer must do to calculate the probablilities of injury. This would be very complicated, and it has to be decided when and if that will be done and when the calculations will be done by the designer. More and more detail can be added to the spreadsheet in subsequent revisions as it is used.

For the calculation of tremor reduction, a design that uses a linear viscous damper and a magnetic particle break will only differ if they have different damping constants. Of course, there are all the cosmetic and size issues aforementioned, but there is also the basic functional issue of which will accomplish the type of damping required more successfully. This issue was not addressed by the spreadsheet as it stands, due to decisions made for simplicity and time constraints. If one desires to use the spreadsheet to do detailed design, these issues must be addressed in the spreadsheet itself. To fully utilize the capabilities of this process, one cannot leave it up to the designer to decide if it will work and then tell the spreadsheet how it works. The spreadsheet must actually evaluate the functionality.

Appendix A
Printout of Design Spreadsheet for the Wrist Orthosis

The following spreadsheet is the one developed for the design of a damped wrist orthosis, as described in previously in this document. The parameter values shown in this printing are for the base line case, or unaided, tremor-inflicted limb.

	Weighted Score	Importance Weight	"GOAL" note	Goal Score
1	0.00	2.00	unobtrusiveness	0.00
2	0.00	3.00	comfort	0.00
3	0.00	3.00	nonenvironcon	0.00
4	0.00	10.00	tremor-reduce	0.00
5	0.00	10.00	safety	0.00
6	0.00	1.00	economy	0.00
7	0.00	3.00	nonperscon	0.00
8	0.00	1.00	failureecon	0.00
9	0.00	2.00	ease-use	0.00
10				

design score: 0.00

```
* "SPECIFICATION" Specification  *
*                         Score  *
**********************************
* unbulky                  0.00  *
*                                *
* functionality            0.00  *
*                                *
* noise                    0.00  *
*                                *
* fit                      0.00  *
*                                *
* coolness                 0.00  *
*                                *
* shapentrlnss             0.00  *
*      ***                       *
* fngrfrdm                 0.00  *
*                                *
* relydays              1000.00  *
*                                *
* tremratio                0.50  *
*                                *
* tremtorque           13500.00  *
*                                *
* damptrem                 1.00  *
*                                *
* purpatten                0.00  *
*                                *
* colormatch               0.00  *
*                                *
* nonfatigue               0.00  *
*                                *
* r.o.m.                   0.00  *
*                                *
* exnonpress               0.00  *
*                                *
* flnonpress               0.00  *
*                                *
```

```
* nonpressure                 0.00  *
*                                   *
* Tskinc                     23.00  *
*                                   *
* radii                       0.00  *
*                                   *
* wcforce                    12.50  *
*                                   *
* wctorque                13450.00  *
*                                   *
* %handrad                    0.00  *
*                                   *
* %radarmrad                  0.00  *
*                                   *
* %latarmrad                  0.00  *
*                                   *
* geocen                      0.00  *
*                                   *
* ltod                        0.00  *

*                                   *
* shearlvl                    0.00  *
*                                   *
* damptorque                  0.00  *
*************************************
```

"DESIGN PARAMETERS"		Parameter Values	Units and notes
devicecolor	*	2.0000	0 to 5, 0 unnatural, bright or shiny color 1 to 5 match color of skin types
noiselvl	*	0.0000	sound pressure level,dB (100 max) (speech ~60 dB, subway ~100 dB)
frequency		0.0000	0 <500 or >10000 hz, -1 500 to 2000 hz or 8000 to 10000 hz, -2 2000 to 8000 hz
noisecntnty	*	0.0000	noise time/cycle time, 0 to 1
lvlfluc		0.0000	does noise level fluctuate at least 10% within one cycle? 0 does not, -1 does
freqfluc		0.0000	does frequency fluctuate at least 10% within one cycle? 0 does not, -1 does
weight	*	0.0000	kilograms (max 3)
handsize *	*	0.0000	max dimension measured out from hand cm (max 4)
armlength *	*	0.0000	length of lower arm used, cm (max 20)
armsize *	*	0.0000	max dimension measured out from arm cm (max 4)
wristsize *	*	0.0000	max dimension measured out from wrist cm (max 4)
flexion **	*	135.0000	flexion, extension comfortably allowed degrees, (max 135)
pronation **	*	180.0000	pronation,supination comfortably allowed lower arm fixed, degrees (max 180)
abduction **	*	90.0000	adduction, abduction comfortably allowed degrees, (max 90)
snaglessness		0.0000	w/ clothing etc. 0 none, -1 slight chance, -2 use caution, -3 snag on loose articles -4 w/clothing or hair,-5 must roll sleeves
probmininj *	*	0.0000	probability of minor, major and catasta-phic injuries. Minor requires no pro-
probmajinj *	*	0.0000	fessional attention, loss of use for time to attend only. Major: prof. atten. and
probcatinj *	*	0.0000	loss of use longer than attendance time. catastrophic: pemanently reduced function.
relytime		************	50% design life, or average time between breakdowns, # of cycles
costfix		0.0000	average estimated cost to fix the more frequent breakdowns
adjustments		0.0000	0to-5, 0 none, -3 adjustments over time, -5 cumbersome number of adjustments
puton		0.0000	-1to-5, -1 slip on, -2 slip on w/ straps -3 partial assembly each time, -4 lots of assembly, -5 requires assistance
sknshear		0.0000	max skinshear per applied muscle torque (N/m^2)/N*m), or 1/m (include gravity)
Kcuff		100000.0000	thermal conductivity of cuff material (W/m degrees C)
cengrav	-	0.0000	location of the center of gravity(max 3) 0, within limb or # cm away from limb

coverage	0.0000	ratio of skin covered to total skin from fingers to end of arm splint
finish	0.0000	% mat's w/ natural, matte, soft finish (0 all, -1 >75%, -2 >50%, -3 >25%, -4 <25%)
backlash	0.0000	backlash in system, radians (max 2)
damping	0.0000	g*cm/s**2*rad/s
minertia	0.0000	moment of inertia that device adds to hand (g*cm**2)
exhandarea *	100000.0000	area of distribution of pressure on top of hand during extension (m^2)
exhandarear *	100000.0000	area of distribution of reaction pressure on bottom of hand during extension(m^2)
exhandlngt *	100000.0000	effective moment arm of pressure on top of hand due to extension(m)
exhandlngtr *	100000.0000	effective moment arm of reaction pressure on bottom of hand due to extension(m)
exarmarea *	100000.0000	area of distibution of pressure on top of arm during extension (m^2)
exarmarear *	100000.0000	area of distribution of reaction pressure on bottom of arm due to extension(m^2)
exarmlngt *	100000.0000	effective moment arm of pressure on top of arm due to extension.(m)
exarmlngtr *	100000.0000	effective moment arm of reaction pressure on bottom of arm due to extension(m)
flhandarea *	100000.0000	flexion, hand bottom
flhandarear *	100000.0000	flexion, hand top
flhandlngt *	100000.0000	flexion, hand bottom
flhandlngtr *	100000.0000	flexion, hand top
flarmarea *	100000.0000	flexion, arm bottom
flarmarear *	100000.0000	flexion, arm top
flarmlngt *	100000.0000	flexion, arm bottom
flarmlngtr *	100000.0000	flexion, arm top
clamppress	0.0000	max pressure applied to limb due to clamping of orthosis. (N/m^2)
seams	0.0000	are there visible seam in the splint? (0 no, 1 yes)
protrusion	0.0000	distance of protrusions from a mean diameter, average of total (cm, max 4)
#protrusion	0.0000	number of protrusions in the above average (max 5)
continuity	0.0000	aside from major attached components, is surface continuous? (1 no, 0 yes)
radarmrad *	2.0000	average radius of curvature on the arm in the radial direction(cm)
latarmrad *	1000.0000	average radius of curvature on the arm in the lateral direction (cm)

handrad *	1.0000	average radius of curvature on the hand (cm)
handltod **	10.0000	length to diameter ratio on the hand
armltod **	8.0000	length to diameter ratio on the arm
handgeocen *	0.0000	distance of geometric center of device from g.c. of hand, at the hand (cm,max 4)
armgeocen *	0.0000	distance of geometric center of device from g.c. of arm, at the arm (cm,max 4)
index **	0.0000	can easily touch index finger to thumb (0 can, 1 can not)
middle **	0.0000	can easily touch middle finger to thumb (0 can, 1 can not)
area *	0.0000	.% area of circle between thumb and forefinger blocked by device
folding *	0.0000	% folding of thumb to palm restricted by device
accdiam **	11.0000	diameter of smallest opening hand and device can enter. (cm)
palmdist **	0.0000	distance of palm from surface while hand is resting on surface. (cm)
writedist **	0.0000	distance of hand from surface while resting in a writing position. (cm)
contrestrict **	0.0000	% area of hand and lower arm that cannot be used as a contact surface.
cost *	0.0000	cost to consumer, includes some standard profit. (dollars)
maxcost *	0.0000	max price that can be charged considering complexity and returned function (dollars)

****

"USER PARAMETERS"	PARAMETER VALUES	NOTES AND UNITS
tremamp *	1.00	rms tremor, radians
tremfreq *	3.00	tremor frequency, hertz
gender	1.00	1 male; 0 female
handinert	1500.00	hand moment of inertia, grams*cm**2
skincolor	2.00	1 to 5 1 very fair, pale skin 2 medium skin, not very dark 3 dark caucasian skin 4 light negro skin 5 dark negro skin
actvness	6.00	scaled value representing activity of user, 1 to 10. A 1 goes to the user that does not use his/her arm to interact with the environment. 5 is average amount (deskworker). 10 is for person who is always interacting with the environment in a highly articulated manner. see notes
maxforce	20.00	maximum force producable at the hand with arm outstretched. (N)
sleevetype	1.00	does the user wear long sleeves? (1 always, 0 otherwise)
opforce	5.00	force produced to hold arm outstretched, length of arm times its weight (N)
uarmlngth	1.00	length of arm, (m)
extorque *	100.00	maximum, voluntary extension torque in the wrist (N*m)
fltorque *	100.00	maximum, voluntary flexion torque in the wrist (N*m)
mxclmppress	40.00	maximum clamping pressure that does not impede blood flow(N/m^2)
skinstress	1000.00	worst stress skin can withstand without injury(min of different values) (N/m^2)
Tamb *	23.00	ambient temperature in which the device will be used, (degrees C)
Tskin *	35.00	skin surface temperatre of user (degrees C)
Tmax *	45.00	maximum acceptable skin surface temperature due to insulation(degrees C)
Tbody *	50.00	body temperature of user (degrees C)
Kskin *	15.00	thermal conductivity of skin (W/m*degrees C)
uhandrad **	1.00	average radius of curvature of hand (cm)
uradarmrad **	2.00	average radius of curvature of arm in the radial direction (cm)
ulatarmrad	1000.00	effective radius of curvature of arm

```
*       **              .          in the lateral direction (cm)           *
*   uhandltod       10.00       length to diameter ratio of hand           *
*       *                                   (average)                      *
*   uarmltod         8.00    length to diameter ratio of lower arm         *
*       *                                   (average)                      *
*    cycles       1000.00       average number of cycles per day           *
*                                                                          *
*     Loss       10000.00      dollar value of loss due to tremor          *
*                                                                          *
*   uaccdiam        11.00   diameter of smallest opening the user's        *
*                                    hand can enter. (cm)                  *
*   maxshear        10.00   maximum acceptable shear stress on skin        *
*                                          (N/m^2)                         *
****************************************************************************
```

Appendix B
List of Goal and Specification Formulas

Design Goal Formulas

Unobtrusiveness
(((COLORMATCH)*2)+((SHAPENTRLNSS)*2)+(NOISE*2)
+(UNBULKY*2)+((FINISH/4)*2))

Comfort
((FIT*3.4)+(COOLNESS*3.3)+(((@MIN (1,SHEARLVL))*-1)*3.3))

Nonenvironcon
((SNAGLESSNESS/5*3)+(FUNCTIONALITY*7))

Tremor-reduce
@IF(DAMPTREM=TREMAMP,0,(@IF(DAMPTREM
<=0.01,10,(TREMRATIO*10))))

Safety
(((PROBMININJ*-1)*3.3)+((PROBCATINJ*-1)
3.3)+((PROBMAJINJ-1)*3.4))

Economy
(@IF((MAXCOST=0),0,(((MAXCOST/2)-COST)/ (MAXCOST/2))*10)))

Nonperscon
((R.O.M.*3.3)+(PURPATTEN*3.3)+(NONFATIGUE*3.4))

Failureecon
(@IF(COSTFIX=0),0,(@IF((TREMRATIO=0),
-10,(@MAX(-10,((-10/0.2)*(COSTFIX/
(TREMRATIO*LOSS*RELYDAYS)))))))))

Ease-use
((5*ADJUSTMENTS/5)+(5*PUTON/5))

Total Design Score Formula

(((UNOBTRUSIVENESS+COMFORT+NONENVIRONCON+
TREMOR-REDUCE+SAFETY+ECONOMY+NONPERSON+
FAILUREECON+EASE-USE)*100)/150)

Specification Formulas

Functionality
(((@IF(((ACCDIAM-UACCDIAM)>UACCDIAM),-1,
((ACCDIAM-UACCDIAM)/-UACCDIAM)))
+(PALMDIST/-4)+(WRITEDIST/-4)+
(CONTRESTRICT/-100)+FNGRFRDM)/5)

Noise
@IF(NOISELVL=0,0,(((NOISELVL/-100)*0.2)
+((FREQUENCY/2)*0.2)+((NOISECNTNTY-1)*0.2)
+(LVLFLUC*0.2)+(FREQFLUC*0.2)))

Fit
((@IF((MXCLMPPRESS=0),0,(@MIN
((CLAMPPRESS/MXCLMPPRESS),1)))*
(-0.5))+(NONPRESSURE*0.5))

Coolness
(((TSKIN-TSKINC)/(TMAX-TSKIN))*COVERAGE)

Shapentrlnss
((SEAMS+((PRUTRUSION*#PROTRUSION)/20)
+CONTINUITY+RADII+GEOCEN+LTOD)/-6)

Fngrfrdm
(((0.4*INDEX)+(0.2*MIDDLE)+(0.2*(AREA/100))
+(0.2*(FOLDING/100)))*-1)

Relydays
(RELYTIME/CYCLES)

Tremratio
((TREMAMP-(DAMPTREM/2))/TREMAMP)

Tremtorque
(HANDINERT*(TREMFREQ^2)*TREMAMP)

Damptrem
(((DAMPING*HANDINERT*TREMFREQ*TREMAMP)
+((MINERTIA+HANDINERT)*HANDINERT*(TREMFREQ^2)
*TREMAMP))/((((MINERTIA+HANDINERT)^2)
*(TREMFREQ^2))+(DAMPING^2)))

Purpatten
@IF((7*(DAMPING/100000))<(0.5*(@MAX
(EXTORQUE,FLTORQUE))),((7*(DAMPING/100000))
/(0.5*(@MAX(EXTORQUE,FLTORQUE))))*-1,-1)

Colormatch

@IF(DEVICECOLOR=0,-1,@IF(DEVICECOLOR=SKINCOLOR,0,
(((@ABS(DEVICECOLOR-SKINCOLOR))/4)*-1)))

Nonfatigue
(@MAX(-1,(((@IF(WEIGHT=0,0((((WEIGHT*UARMLNGTH)
+OPFORCE)/WCFORCE)*0.5)))+((@MIN(1,((DAMPING*
TREMFREQ)/WCTORQUE)))*0.5))*-1)))

R.O.M.
(((((135-FLEXION)/135)*0.6)+(((180-PRONATION)
/180)*0.3)+(((90-ABDUCTION)/90)*0/1))*-1)

Exnonpress
((@MIN(1,((DAMPTORQUE/(EXHANDLNGT*
EXHANDAREA))/SKINSTRESS)))
+(@MIN(1,((DAMPTORQUE/(EXARMLNGT*
EXARMAREA))/SKINSTRESS)))
+(@MIN(1,((DAMPTORQUE/(EXHANDLNGTR*
EXHANDAREAR))/SKINSTRESS)))
+(@MIN(1,((DAMPTORQUE/(EXARMLNGTR*
EXARMAREAR))/SKINSTRESS))))

Flnonpress
((@MIN(1,((DAMPTORQUE/(FLARMLNGT*
FLARMAREA))/SKINSTRESS)))
+(@MIN(1,((DAMPTROQUE/(FLHANDLNGT*
FLHANDAREA))/SKINSTRESS)))
+(@MIN(1,((DAMPTORQUE/(FLARMLNGTR*
FLARMAREAR))/SKINSTRESS)))
+(@MIN(1,((DAMPTORQUE/(FLHANDLNGTR*
FLAREAR))/SKINSTRESS))))

Nonpressure
((EXNONPRESS*0.5)+(FLNONPRESS*0.5))

Tskinc
(@MIN(TMAX,((TBODY/KCUFF)+(TAMB/KSKIN))
/((1/KCUFF)+(1/KSKIN))))

Radii
(@AVG(@IF((%HANDRAD<0.1),0,@IF
((%HANDRAD>0.8),1,%HANDRAD))
,@IF((%RADARMRAD<0.1),0,@IF
((%RADARMRAD>0.8),1,%RADARMRAD))
,@IF((%LATARMARAD<0.1),0,@IF
((%LATARMRAD>0.8),1,%LATARMRAD))))

Wcforce
(OPFORCE+(@ABS(MAXFORCE-OPFORCE)/2))

Wctorque
((TREMTORQUE+(@ABS(@MIN(EXTORQUE,
FLTORQUE)-TREMTORQUE))/2))

%handrad
(@ABS(UHANDRAD-HANDRAD)/UHANDRAD)

%radarmrad
(@ABS(URADARMRAD-RADARMRAD)/URADARMRAD)

%latarmrad
(@ABS(ULATARMRAD-LATARMRAD)/ULATARMRAD)

Geocen
(((ARMGEOCEN/4)*0.5)+((HANDGEOCEN/4)*0.5))

Ltod
(((@IF(((@ABS(UHANDLTOD-HANDLTOD)/UHANDLTOD)<0.1)
,0,@IF(((@ABS(UH
ANDLTOD-HANDLTOD)/UHANDLTOD)>0.8),1
,((@ABS(UHANDLTOD-HANDLTOD)/UHANDLTOD)))))*0.5)+
((@IF(((@ABS(UARMLTOD-ARMLTOD)/UARMLTOD)<0.1),0,
@IF(((@ABS(UARMLTOD-ARMLTOD)/UARMLTOD)))))*0.5)))

Shearlvl
((@MAX(FLTORQUE,EXTORQUE)*SKNSHEAR)/MAXSHEAR)

Damptorque
((7*DAMPING)/100000)

Appendix C
Spreadsheet With Values for Proposed Designs

The following printouts of the spreadsheet contain the design and user parameter values for the three proposed designs.

Design #1

	Weighted Score	Importance Weight	"GOAL"	Goal Score
			note	
1	-5.05	2.00	unobtrusiveness	-2.53
2	-20.81	3.00	comfort	-6.94
3	-12.05	3.00	nonenvironcon	-4.02
4	72.94	10.00	tremor-reduce	7.29
5	-2.32	10.00	safety	-0.23
6	0.00	1.00	economy	0.00
7	-11.40	3.00	nonpersoon	-3.80
8	-0.09	1.00	failurecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 10.21

```
* "SPECIFICATION" Specification  *
*                         Score  *
***********************************
* unbulky                 -0.40  *
*                                *
* functionality           -0.23  *
*                                *
* noise                    0.00  *
*                                *
* fit                     -0.39  *
*                                *
* coolness                -0.70  *
*                                *
* shapentrlnss            -0.11  *
*       ***                      *
* fngrfrdm                -0.14  *
*                                *
* relydays                50.00  *
*                                *
* tremratio                0.73  *
*                                *
* tremtorque           13500.00  *
*                                *
* damptrem                 0.54  *
*                                *
* purpatten               -0.01  *
*                                *
* colormatch              -0.25  *
*                                *
* nonfatigue              -0.71  *
*                                *
* r.o.m.                  -0.41  *
*                                *
* exnonpress              -0.50  *
*                                *
```

```
* flnonpress                    -0.56  *
*                                      *
* nonpressure                   -0.53  *
*                                      *
* Tskinc                        45.00  *
*                                      *
* radii                          0.17  *
*                                      *
* wcforce                       12.50  *
*                                      *
* wctorque                   13450.00  *
*                                      *
* %handrad                       0.00  *
*                                      *
* %radarmrad                     0.50  *
*                                      *
* %latarmrad                     0.05  *
*                                      *
* geocen                         0.13  *
*                                      *
* ltod                           0.19  *
*                                      *
* shearlvl                     100.00  *
*                                      *
* damptorque                     0.70  *
****************************************
```

"DESIGN PARAMETERS"	Parameter Values	Units and notes
devicecolor	1.0000	0 to 5, 0 unnatural, bright or shiny color 1 to 5 match color of skin types
noiselvl	0.0000	sound pressure level,dB (100 max) (speech ~60 dB, subway ~100 dB)
frequency	0.0000	0 <500 or >10000 hz, -1 500 to 2000 hz or 8000 to 10000 hz, -2 2000 to 8000 hz
noisecntnty	0.0000	noise time/cycle time, 0 to 1
lvlfluc	0.0000	does noise level fluctuate at least 10% within one cycle? 0 does not, -1 does
freqfluc	0.0000	does frequency fluctuate at least 10% within one cycle? 0 does not, -1 does
weight	0.2500	kilograms (max 3)
handsize *	1.5000	max dimension measured out from hand cm (max 4)
armlength *	15.0000	length of lower arm used, cm (max 20)
armsize *	2.0000	max dimension measured out from arm cm (max 4)
wristsize *	2.0000	max dimension measured out from wrist cm (max 4)
flexion **	100.0000	flexion, extension comfortably allowed degrees, (max 135)
pronation **	90.0000	pronation,supination comfortably allowed lower arm fixed, degrees (max 180)
abduction **	0.0000	adduction, abduction comfortably allowed degrees, (max 90)
snaglessness	-4.0000	w/ clothing etc. 0 none, -1 slight chance, -2 use caution, -3 snag on loose articles -4 w/clothing or hair,-5 must roll sleeves
probmininj *	0.0500	probability of minor, major and catasta- phic injuries. Minor requires no pro-
probmajinj *	0.0100	fessional attention, loss of use for time to attend only. Major: prof. atten. and
probcatinj *	0.0100	loss of use longer than attendance time. catastrophic: pemanently reduced function.
relytime	50000.0000	50% design life, or average time between breakdowns, # of cycles
costfix	5.0000	average estimated cost to fix the more frequent breakdowns
adjustments	-1.0000	0to-5, 0 none, -3 adjustments over time, -5 cumbersome number of adjustments
puton	-2.0000	-1to-5, -1 slip on, -2 slip on w/ straps -3 partial assembly each time, -4 lots of assembly, -5 requires assistance
sknshear	10.0000	max skinshear per applied muscle torque (N/m^2)/N*m), or 1/m (include gravity)
Kcuff	0.0020	thermal conductivity of cuff material (W/m degree C)
cengrav	0.0000	location of the center of gravity(max 8) 0, within limb or # cm away from limb

coverage	0.7000	ratio of skin covered to total skin from fingers to end of arm splint
finish	-2.0000	% mat's w/ natural, matte, soft finish (0 all, -1 >75%, -2 >50%, -3 >25%, -4 <25%)
backlash	0.0100	backlash in system, radians (max 2)
damping	10000.0000	g*cm/s**2*rad/s
minertia	100.0000	moment of inertia that device adds to hand (g*cm**2)
exhandarea *	0.0400	area of distribution of pressure on top of hand during extension (m^2)
exhandarear *	0.0240	area of distribution of reaction pressure on bottom of hand during extension(m^2)
exhandlngt *	0.0300	effective moment arm of pressure on top of hand due to extension(m)
exhandlngtr *	0.0200	effective moment arm of reaction pressure on bottom of hand due to extension(m)
exarmarea *	0.0600	area of distibution of pressure on top of arm during extension (m^2)
exarmarear *	0.0600	area of distribution of reaction pressure on bottom of arm due to extension(m^2)
exarmlngt *	0.1000	effective moment arm of pressure on top of arm due to extension.(m)
exarmlngtr *	0.0400	effective moment arm of reaction pressure on bottom of arm due to extension(m)
flhandarea *	0.0400	flexion, hand bottom
flhandarear *	0.0240	flexion, hand top
flhandlngt *	0.0200	flexion, hand bottom
flhandlngtr *	0.0300	flexion, hand top
flarmarea *	0.0600	flexion, arm bottom
flarmarear *	0.0600	flexion, arm top
flarmlngt *	0.1000	flexion, arm bottom
flarmlngtr *	0.0400	flexion, arm top
clamppress	10.0000	max pressure applied to limb due to clamping of orthosis. (N/m^2)
seams	0.0000	are there visible seam in the splint? (0 no, 1 yes)
protrusion	2.0000	distance of protrusions from a mean diameter, average of total (cm, max 4)
#protrusion	2.0000	number of protrusions in the above average (max 5)
continuity	0.0000	aside from major attached components, is surface continuous? (1 no, 0 yes)
radarmrad *	1.0000	average radius of curvature on the arm in the radial direction(cm)
latarmrad *	1050.0000	average radius of curvature on the arm in the lateral direction (cm)

handrad *	1.0000	average radius of curvature on the hand (cm)
handltod **	10.0000	length to diameter ratio on the hand
armltod **	5.0000	length to diameter ratio on the arm
handgeocen *	0.0000	distance of geometric center of device from g.c. of hand, at the hand (cm,max 4)
armgeocen *	1.0000	distance of geometric center of device from g.c. of arm, at the arm (cm,max 4)
index **	0.0000	can easily touch index finger to thumb (0 can, 1 can not)
middle **	0.0000	can easily touch middle finger to thumb (0 can, 1 can not)
area *	20.0000	% area of circle between thumb and forefinger blocked by device
folding *	50.0000	% folding of thumb to palm restricted by device
accdiam **	15.0000	diameter of smallest opening hand and device can enter. (cm)
palmdist **	0.5000	distance of palm from surface while hand is resting on surface. (cm)
writedist **	0.5000	distance of hand from surface while resting in a writing position. (cm)
contrestrict **	40.0000	% area of hand and lower arm that cannot be used as a contact surface.
cost *	500.0000	cost to consumer, includes some standard profit. (dollars)
maxcost *	1000.0000	max price that can be charged considering complexity and returned function (dollars)

****

"USER PARAMETERS"	PARAMETER VALUES	NOTES AND UNITS
tremamp	1.00	rms tremor, radians
tremfreq	3.00	tremor frequency, hertz
gender	1.00	1 male; 0 female
handinert	1500.00	hand moment of inertia, grams*cm**2
skincolor	2.00	1 to 5 1 very fair, pale skin 2 medium skin, not very dark 3 dark caucasian skin 4 light negro skin 5 dark negro skin
actvness	6.00	scaled value representing activity of user, 1 to 10. A 1 goes to the user that does not use his/her arm to interact with the environment. 5 is average amount (deskworker). 10 is for person who is always interacting with the environment in a highly articulated manner. see notes
maxforce	20.00	maximum force producable at the hand with arm outstretched. (N)
sleevetype	1.00	does the user wear long sleeves? (1 always, 0 otherwise)
opforce	5.00	force produced to hold arm outstretched, length of arm times its weight (N)
uarmlngth	1.00	length of arm, (m)
extorque	100.00	maximum, voluntary extension torque in the wrist (N*m)
fltorque	100.00	maximum, voluntary flexion torque in the wrist (N*m)
mxclmppress	40.00	maximum clamping pressure that does not impede blood flow(N/m^2)
skinstress	1000.00	worst stress skin can withstand without injury(min of different values) (N/m^2)
Tamb	23.00	ambient temperature in which the device will be used, (degrees C)
Tskin	35.00	skin surface temperatre of user (degrees C)
Tmax	45.00	maximum acceptable skin surface temperature due to insulation(degrees C)
Tbody	50.00	body temperature of user (degrees C)
Kskin	15.00	thermal conductivity of skin (W/m*degrees C)
uhandrad	1.00	average radius of curvature of hand (cm)
uradarmrad	2.00	average radius of curvature of arm in the radial direction (cm)
ulatarmrad	1000.00	effective radius of curvature of arm

```
*        **                      in the lateral direction (cm)          *
*   uhandltod      10.00      length to diameter ratio of hand          *
*        *                               (average)                      *
*   uarmltod        8.00    length to diameter ratio of lower arm       *
*        *                               (average)                      *
*    cycles      1000.00      average number of cycles per day          *
*                                                                       *
*     Loss      10000.00     dollar value of loss due to tremor         *
*                                                                       *
*   uaccdiam       11.00   diameter of smallest opening the user's      *
*                                 hand can enter. (cm)                  *
*   maxshear       10.00   maximum acceptable shear stress on skin      *
*                                      (N/m^2)                          *
*************************************************************************
```

Design #2

	Weighted Score	Importance Weight	"GOAL"	Goal Score
			note	
1	-3.45	2.00	unobtrusiveness	-1.73
2	-20.22	3.00	comfort	-6.74
3	-6.23	3.00	nonenvironcon	-2.08
4	72.94	10.00	tremor-reduce	7.29
5	-1.99	10.00	safety	-0.20
6	0.00	1.00	economy	0.00
7	-11.38	3.00	nonperscon	-3.79
8	-0.00	1.00	failureecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 15.78

"SPECIFICATION" Specification	Score
unbulky	-0.28
functionality	-0.21
noise	0.00
fit	-0.53
coolness	-0.50
shapentrlnss	-0.09
***	
fngrfrdm	-0.14
relydays	100.00
tremratio	0.73
tremtorque	13500.00
damptrem	0.54
purpatten	-0.01
colormatch	-0.25
nonfatigue	-0.71
r.o.m.	-0.41
exnonpress	-0.90

```
*  flnonpress                          -0.96  *
*                                             *
*  nonpressure                         -0.93  *
*                                             *
*  Tskinc                              45.00  *
*                                             *
*  radii                                0.17  *
*                                             *
*  wcforce                             12.50  *
*                                             *
*  wctorque                         13450.00  *
*                                             *
*  %handrad                             0.00  *
*                                             *
*  %radarmrad                           0.50  *
*                                             *
*  %latarmrad                           0.05  *
*                                             *
*  geocen                               0.13  *
*                                             *
*  ltod                                 0.19  *

*                                             *
*  shearlvl                           100.00  *
*                                             *
*  damptorque                           0.70  *
**********************************************
```

"DESIGN PARAMETERS	Parameter Values	Units and notes
devicecolor	1.0000	0 to 5, 0 unnatural, bright or shiny color 1 to 5 match color of skin types
noiselvl	0.0000	sound pressure level,dB (100 max) (speech ~60 dB, subway ~100 dB)
frequency	0.0000	0 <500 or >10000 hz, -1 500 to 2000 hz or 8000 to 10000 hz, -2 2000 to 8000 hz
noisecntnty	0.0000	noise time/cycle time, 0 to 1
lvlfluc	0.0000	does noise level fluctuate at least 10% within one cycle? 0 does not, -1 does
freqfluc	0.0000	does frequency fluctuate at least 10% within one cycle? 0 does not, -1 does
weight	0.2000	kilograms (max 3)
handsize *	0.2500	max dimension measured out from hand cm (max 4)
armlength *	15.0000	length of lower arm used, cm (max 20)
armsize *	2.0000	max dimension measured out from arm cm (max 4)
wristsize *	2.0000	max dimension measured out from wrist cm (max 4)
flexion **	100.0000	flexion, extension comfortably allowed degrees, (max 135)
pronation **	90.0000	pronation,supination comfortably allowed lower arm fixed, degrees (max 180)
abduction **	0.0000	adduction, abduction comfortably allowed degrees, (max 90)
snaglessness	-1.0000	w/ clothing etc. 0 none, -1 slight chance, -2 use caution, -3 snag on loose articles -4 w/clothing or hair,-5 must roll sleeves
probmininj *	0.0400	probability of minor, major and catasta-
probmajinj *	0.0100	phic injuries. Minor requires no pro- fessional attention, loss of use for time to attend only. Major: prof. atten. and
probcatinj *	0.0100	loss of use longer than attendance time. catastrophic: pemanently reduced function.
relytime	100000.0000	50% design life, or average time between breakdowns, # of cycles
costfix	5.0000	average estimated cost to fix the more frequent breakdowns
adjustments	-1.0000	0to-5, 0 none, -3 adjustments over time, -5 cumbersome number of adjustments
puton	-2.0000	-1to-5, -1 slip on, -2 slip on w/ straps -3 partial assembly each time, -4 lots of assembly, -5 requires assistance
sknshear	10.0000	max skinshear per applied muscle torque (N/m^2)/N*m), or 1/m (include gravity)
Kcuff	0.0020	thermal conductivity of cuff material (W/m degree C)
cengrav *	0.0000	location of the center of gravity(max 3) 0, within limb or # cm away from limb

coverage	0.5000	ratio of skin covered to total skin from fingers to end of arm splint
finish	-1.0000	% mat's w/ natural, matte, soft finish (0 all,-1 >75%,-2 >50%,-3 >25%,-4 <25%)
backlash	0.0100	backlash in system, radians (max 2)
damping	10000.0000	g*cm/s**2*rad/s
minertia	100.0000	moment of inertia that device adds to hand (g*cm**2)
exhandarea *	0.0400	area of distribution of pressure on top of hand during extension (m^2)
exhandarear *	0.0240	area of distribution of reaction pressure on bottom of hand during extension(m^2)
exhandlngt *	0.0300	effective moment arm of pressure on top of hand due to extension(m)
exhandlngtr *	0.0300	effective moment arm of reaction pressure on bottom of hand due to extension(m)
exarmarea *	0.0016	area of distibution of pressure on top of arm during extension (m^2)
exarmarear *	0.0016	area of distribution of reaction pressure on bottom of arm due to extension(m^2)
exarmlngt *	0.0120	effective moment arm of pressure on top of arm due to extension.(m)
exarmlngtr *	0.0400	effective moment arm of reaction pressure on bottom of arm due to extension(m)
flhandarea *	0.0400	flexion, hand bottom
flhandarear *	0.0240	flexion, hand top
flhandlngt *	0.0200	flexion, hand bottom
flhandlngtr *	0.0300	flexion, hand top
flarmarea *	0.0016	flexion, arm bottom
flarmarear *	0.0016	flexion, arm top
flarmlngt *	0.0400	flexion, arm bottom
flarmlngtr *	0.0120	flexion, arm top
clamppress	5.0000	max pressure applied to limb due to clamping of orthosis. (N/m^2)
seams	0.0000	are there visible seam in the splint? (0 no, 1 yes)
protrusion	1.0000	distance of protrusions from a mean diameter, average of total (cm, max 4)
#protrusion	1.0000	number of protrusions in the above average (max 5)
continuity	0.0000	aside from major attached components, is surface continuous? (1 no, 0 yes)
radarmrad *	1.0000	average radius of curvature on the arm in the radial direction(cm)
latarmrad *	1050.0000	average radius of curvature on the arm in the lateral direction (cm)

handrad *	1.0000	average radius of curvature on the hand (cm)
handltod **	10.0000	length to diameter ratio on the hand
armltod **	5.0000	length to diameter ratio on the arm
handgeocen *	0.0000	distance of geometric center of device from g.c. of hand, at the hand (cm,max 4)
armgeocen *	1.0000	distance of geometric center of device from g.c. of arm, at the arm (cm,max 4)
index **	0.0000	can easily touch index finger to thumb (0 can, 1 can not)
middle **	0.0000	can easily touch middle finger to thumb (0 can, 1 can not)
area *	20.0000	% area of circle between thumb and forefinger blocked by device
folding *	50.0000	% folding of thumb to palm restricted by device
accdiam **	15.0000	diameter of smallest opening hand and device can enter. (cm)
palmdist **	0.5000	distance of palm from surface while hand is resting on surface. (cm)
writedist **	0.5000	distance of hand from surface while resting in a writing position. (cm)
contrestrict **	30.0000	% area of hand and lower arm that cannot be used as a contact surface.
cost *	500.0000	cost to consumer, includes some standard profit. (dollars)
maxcost *	000.0000	max price that can be charged considering complexity and returned function (dollars)

****

"USER PARAMETERS"	PARAMETER VALUES	NOTES AND UNITS
tremamp *	1.00	rms tremor, radians
tremfreq *	3.00	tremor frequency, hertz
gender	1.00	1 male; 0 female
handinert	1500.00	hand moment of inertia, grams*cm**2
skincolor	2.00	1 to 5 1 very fair, pale skin 2 medium skin, not very dark 3 dark caucasian skin 4 light negro skin 5 dark negro skin
actvness	6.00	scaled value representing activity of user, 1 to 10. A 1 goes to the user that does not use his/her arm to interact with the environment. 5 is average amount (deskworker). 10 is for person who is always interacting with the environment in a highly articulated manner. see notes
maxforce	20.00	maximum force producable at the hand with arm outstretched. (N)
sleevetype	1.00	does the user wear long sleeves? (1 always, 0 otherwise)
opforce	5.00	force produced to hold arm outstretched, length of arm times its weight (N)
uarmlngth	1.00	length of arm, (m)
extorque *	100.00	maximum, voluntary extension torque in the wrist (N*m)
fltorque *	100.00	maximum, voluntary flexion torque in the wrist (N*m)
mxclmppress	40.00	maximum clamping pressure that does not impede blood flow(N/m^2)
skinstress	1000.00	worst stress skin can withstand without injury(min of different values) (N/m^2)
Tamb *	23.00	ambient temperature in which the device will be used, (degrees C)
Tskin *	35.00	skin surface temperatre of user (degrees C)
Tmax *	45.00	maximum acceptable skin surface temperature due to insulation(degrees C)
Tbody *	50.00	body temperature of user (degrees C)
Kskin *	15.00	thermal conductivity of skin (W/m*degrees C)
uhandrad **	1.00	average radius of curvature of hand (cm)
uradarmrad **	2.00	average radius of curvature of arm in the radial direction (cm)
ulatarmrad	1000.00	effective radius of curvature of arm

```
*        **                   in the lateral direction (cm)          *
*   uhandltod      10.00     length to diameter ratio of hand        *
*        *                              (average)                    *
*   uarmltod        8.00   length to diameter ratio of lower arm     *
*        *                              (average)                    *
*    cycles      1000.00     average number of cycles per day        *
*                                                                    *
*     Loss      10000.00    dollar value of loss due to tremor       *
*                                                                    *
*   uaccdiam       11.00  diameter of smallest opening the user's    *
*                                hand can enter. (cm)                *
*   maxshear       10.00  maximum acceptable shear stress on skin.   *
*                                      (N/m^2)                       *
**********************************************************************
```

Design #3

	Weighted Score	Importance Weight	"GOAL"	Goal Score
			note	
1	-4.83	2.00	unobtrusiveness	-2.41
2	-22.20	3.00	comfort	-7.40
3	-6.23	3.00	nonenvironcon	-2.08
4	72.94	10.00	tremor-reduce	7.29
5	-1.99	10.00	safety	-0.20
6	0.00	1.00	economy	0.00
7	-11.46	3.00	nonperscon	-3.82
8	-0.00	1.00	failureecon	-0.00
9	-6.00	2.00	ease-use	-3.00
10				

design score: 13.49

"SPECIFICATION"	Specification Score
unbulky	-0.40
functionality	-0.21
noise	0.00
fit	-0.53
coolness	-0.70
shapentrlnss	-0.06
***	
fngrfrdm	-0.14
relydays	50.00
tremratio	0.73
tremtorque	13500.00
damptrem	0.54
purpatten	-0.01
colormatch	-0.25
nonfatigue	-0.72
r.o.m.	-0.41

```
*  exnonpress                        -0.90  *
*                                           *
*  flnonpress                        -0.96  *
*                                           *
*  nonpressure                       -0.93  *
*                                           *
*  Tskinc                            45.00  *
*                                           *
*  radii                              0.17  *
*                                           *
*  wcforce                           12.50  *
*                                           *
*  wctorque                       13450.00  *
*                                           *
*  %handrad                           0.00  *
*                                           *
*  %radarmrad                         0.50  *
*                                           *
*  %latarmrad                         0.05  *
*                                           *
*  geocen                             0.13  *
*                                           *
*  ltod                               0.00  *
*                                           *
*  shearlvl                         100.00  *
*                                           *
*  damptorque                         0.70  *
*********************************************
```

"DESIGN PARAMETERS	Parameter Values	Units and notes
devicecolor	1.0000	0 to 5, 0 unnatural, bright or shiny color 1 to 5 match color of skin types
noiselvl	0.0000	sound pressure level,dB (100 max) (speech ~60 dB, subway ~100 dB)
frequency	0.0000	0 <500 or >10000 hz, -1 500 to 2000 hz or 8000 to 10000 hz, -2 2000 to 8000 hz
noisecntnty	0.0000	noise time/cycle time, 0 to 1
lvlfluc	0.0000	does noise level fluctuate at least 10% within one cycle? 0 does not, -1 does
freqfluc	0.0000	does frequency fluctuate at least 10% within one cycle? 0 does not, -1 does
weight	0.4000	kilograms (max 3)
handsize *	0.2500	max dimension measured out from hand cm (max 4)
armlength *	10.0000	length of lower arm used, cm (max 20)
armsize *	3.0000	max dimension measured out from arm cm (max 4)
wristsize *	3.0000	max dimension measured out from wrist cm (max 4)
flexion **	100.0000	flexion, extension comfortably allowed degrees, (max 135)
pronation **	90.0000	pronation,supination comfortably allowed lower arm fixed, degrees (max 180)
abduction **	0.0000	adduction, abduction comfortably allowed degrees, (max 90)
snaglessness	-1.0000	w/ clothing etc. 0 none, -1 slight chance, -2 use caution, -3 snag on loose articles -4 w/clothing or hair,-5 must roll sleeves
probmininj *	0.0400	probability of minor, major and catasta-phic injuries. Minor requires no pro-
probmajinj *	0.0100	fessional attention, loss of use for time to attend only. Major: prof. atten. and
probcatinj *	0.0100	loss of use longer than attendance time. catastrophic: pemanently reduced function.
relytime	50000.0000	50% design life, or average time between breakdowns, # of cycles
costfix	10.0000	average estimated cost to fix the more frequent breakdowns
adjustments	-1.0000	0to-5, 0 none, -3 adjustments over time, -5 cumbersome number of adjustments
puton	-2.0000	-1to-5, -1 slip on, -2 slip on w/ straps -3 partial assembly each time, -4 lots of assembly, -5 requires assistance
sknshear	10.0000	max skinshear per applied muscle torque (N/m^2)/N*m), or 1/m (include gravity)
Kcuff	0.0020	thermal conductivity of cuff material (W/m degree C)
cengrav	1.0000	location of the center of gravity(max 3) 0, within limb or # cm away from limb

coverage	0.7000	ratio of skin covered to total skin from fingers to end of arm splint
finish	-2.0000	% mat's w/ natural, matte, soft finish (0 all,-1 >75%,-2 >50%,-3 >25%,-4 <25%)
backlash	0.0100	backlash in system, radians (max 2)
damping	10000.0000	g*cm/s**2*rad/s
minertia	100.0000	moment of inertia that device adds to hand (g*cm**2)
exhandarea *	0.0400	area of distribution of pressure on top of hand during extension (m^2)
exhandarear *	0.0240	area of distribution of reaction pressure on bottom of hand during extension(m^2)
exhandlngt *	0.0300	effective moment arm of pressure on top of hand due to extension(m)
exhandlngtr *	0.0200	effective moment arm of reaction pressure on bottom of hand due to extension(m)
exarmarea *	0.0016	area of distibution of pressure on top of arm during extension (m^2)
exarmarear *	0.0016	area of distribution of reaction pressure on bottom of arm due to extension(m^2)
exarmlngt *	0.0120	effective moment arm of pressure on top of arm due to extension.(m)
exarmlngtr *	0.0400	effective moment arm of reaction pressure on bottom of arm due to extension(m)
flhandarea *	0.0400	flexion, hand bottom
flhandarear *	0.0240	flexion, hand top
flhandlngt *	0.0200	flexion, hand bottom
flhandlngtr *	0.0300	flexion, hand top
flarmarea *	0.0016	flexion, arm bottom
flarmarear *	0.0016	flexion, arm top
flarmlngt *	0.0400	flexion, arm bottom
flarmlngtr *	0.0120	flexion, arm top
clamppress	5.0000	max pressure applied to limb due to clamping of orthosis. (N/m^2)
seams	0.0000	are there visible seam in the splint? (0 no, 1 yes)
protrusion	1.0000	distance of protrusions from a mean diameter, average of total (cm, max 4)
#protrusion	1.0000	number of protrusions in the above average (max 5)
continuity	0.0000	aside from major attached components, is surface continuous? (1 no, 0 yes)
radarmrad *	1.0000	average radius of curvature on the arm in the radial direction(cm)
latarmrad *	1050.0000	average radius of curvature on the arm in the lateral direction (cm)

handrad	1.0000	average radius of curvature on the
*		hand (cm)
handltod	10.0000	length to diameter ratio on the hand
**		
armltod	8.0000	length to diameter ratio on the arm
**		
handgeocen	0.0000	distance of geometric center of device
*		from g.c. of hand, at the hand (cm,max 4)
armgeocen	1.0000	distance of geometric center of device
*		from g.c. of arm, at the arm (cm,max 4)
index	0.0000	can easily touch index finger to thumb
**		(0 can, 1 can not)
middle	0.0000	can easily touch middle finger to thumb
**		(0 can, 1 can not)
area	20.0000	% area of circle between thumb and
*		forefinger blocked by device
folding	50.0000	% folding of thumb to palm restricted
*		by device
accdiam	15.0000	diameter of smallest opening hand and
**		device can enter. (cm)
palmdist	0.5000	distance of palm from surface while hand
**		is resting on surface. (cm)
writedist	0.5000	distance of hand from surface while
**		resting in a writing position. (cm)
contrestrict	30.0000	% area of hand and lower arm that cannot
**		be used as a contact surface.
cost	500.0000	cost to consumer, includes some standard
*		profit. (dollars)
maxcost	1000.0000	max price that can be charged considering
*		complexity and returned function (dollars)

"USER PARAMETERS"	PARAMETER VALUES	NOTES AND UNITS
tremamp	1.00	rms tremor, radians
*		
tremfreq	3.00	tremor frequency, hertz
*		
gender	1.00	1 male; 0 female
handinert	1500.00	hand moment of inertia, grams*cm**2
skincolor	2.00	1 to 5
		1 very fair, pale skin
		2 medium skin, not very dark
		3 dark caucasian skin
		4 light negro skin
		5 dark negro skin
actvness	6.00	scaled value representing activity of user, 1 to 10. A 1 goes to the user that does not use his/her arm to interact with the environment. 5 is average amount (deskworker). 10 is for person who is always interacting with the environment in a highly articulated manner. see notes
maxforce	20.00	maximum force producable at the hand with arm outstretched. (N)
sleevetype	1.00	does the user wear long sleeves? (1 always, 0 otherwise)
opforce	5.00	force produced to hold arm outstretched, length of arm times its weight (N)
uarmlngth	1.00	length of arm, (m)
extorque	100.00	maximum, voluntary extension torque
*		in the wrist (N*m)
fltorque	100.00	maximum, voluntary flexion torque
*		in the wrist (N*m)
mxclmppress	40.00	maximum clamping pressure that does not impede blood flow(N/m^2)
skinstress	1000.00	worst stress skin can withstand without injury(min of different values) (N/m^2)
Tamb	23.00	ambient temperature in which the
*		device will be used, (degrees C)
Tskin	35.00	skin surface temperatre of user
*		(degrees C)
Tmax	45.00	maximum acceptable skin surface
*		temperature due to insulation(degrees C)
Tbody	50.00	body temperature of user
*		(degrees C)
Kskin	15.00	thermal conductivity of skin
*		(W/m*degrees C)
uhandrad	1.00	average radius of curvature of hand
**		(cm)
uradarmrad	2.00	average radius of curvature of arm
**		in the radial direction (cm)
ulatarmrad	1000.00	effective radius of curvature of arm

```
*     **                         in the lateral direction (cm)          *
*   uhandltod       10.00      length to diameter ratio of hand         *
*       *                                 (average)                     *
*   uarmltod         8.00    length to diameter ratio of lower arm      *
*       *                                 (average)                     *
*    cycles       1000.00      average number of cycles per day         *
*                                                                       *
*     Loss       10000.00     dollar value of loss due to tremor        *
*                                                                       *
*   uaccdiam        11.00   diameter of smallest opening the user's     *
*                                    hand can enter. (cm)               *
*   maxshear        10.00   maximum acceptable shear stress on skin     *
*                                          (N/m^2)                      *
*************************************************************************
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Appendix D
Other References

The works cited here were used in writing the spreadsheet and formulas, but are not refferred to in the text.

- Woodson, Human Factors Design Handbook, McGraw-Hill, New Youk, 1981
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- Bazorsky, Igor Reliability Theory and Practice, Prentice-Hall, Englewood Cliffs, N.J., 1961
- Dunfee, David E., Suppression of Intention Tremor by Mechanical Loading, Masters Thesis, M.I.T., Cambridge, MA