DESIGN OF A HAND-HELD USER INTERFACE FOR THE ACTIVE JOINT BRACE

by

CHRISTOPHER P. POSSINGER

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the
Degree of

Bachelors of Science in Mechanical Engineering

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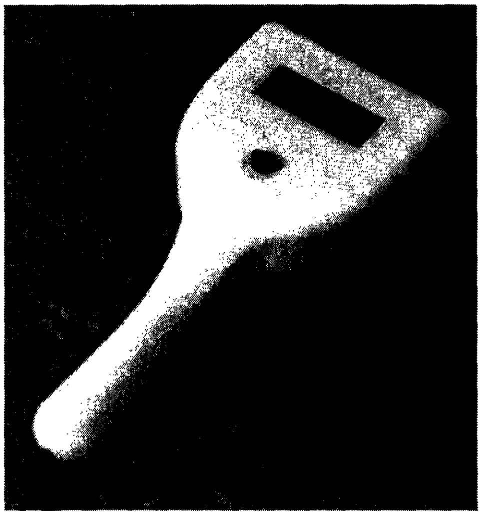
ABSTRACT

The continued development of the Active Joint Brace, a powered orthosis, required that a suitable user interface be designed to control the brace. Since the brace is an electronically-controlled mechanical, medical device, it was important that the user interface (UI) provide both a proper interface to the software that controls the brace, and be in conformance with human factors data.

The constraints provided by the existing electronics and software of the brace, combined with suitable ergonomic data, were used to inform the design of a hand-held user interface device, pictured below. The UI features one-handed operation, utilizing an LCD character display and speaker for output devices and a navigation switch for an input device. In preparation for the new UI, the existing menu system was also reorganized for ease-of-use. In preliminary user testing within the development team, the UI has been judged as satisfactory, with only a few minor changes needed to the enclosure.



Thesis Supervisor: Woodie C. Flowers
Title: Pappalardo Professor of Mechanical Engineering

Biographical Note

Christopher Possinger is a native of Omaha, Nebraska, and while at the Massachusetts Institute of Technology he lived on Third East, East Campus, his entire undergraduate career (August 2000 to June 2005). His concentration in Course 2 is product design, and his humanities concentration is Visual Arts. Mr. Possinger was led to his thesis project by working on an Undergraduate Research Opportunity within the Active Joint Brace group over the summer and fall of 2004. After graduating, Mr. Possinger plans to work either in a product design firm or within a company known for their product design, hopefully in the Boston area. An online portfolio of his design projects is currently available at http://spling.mit.edu/projects.

Table of Contents

Table of Figures

1.0 Introduction

In order to further the development of the Active Joint Brace[1], a user interface has been designed that attempts to fit the needs of all possible end users, from the engineers working on the project to the patients wearing the brace. This device, pictured below in **Figure 1**, is designed to be as easy to use as possible, while at the same time conforming to the human factors recommendations. Since the brace is a medical device, the importance of human factors cannot be understated, and, as a device for assisting the handicapped, the ease of use is also underlined.

The user interface, or UI, for the Active Joint Brace is based around the brace's existing software, and so, in designing the interface, the first task was to define the human interface to that software. Once the parts making up that interface had been defined, the next task was to construct an enclosure to house all of these different parts, ensuring that they are all properly placed according to the constraints of human factors data. Finally, the interface between the software and the human, the menu system that sorts the variables which the user can control, was reviewed and optimized for ease of use. The outcomes of these tasks defines the user interface.

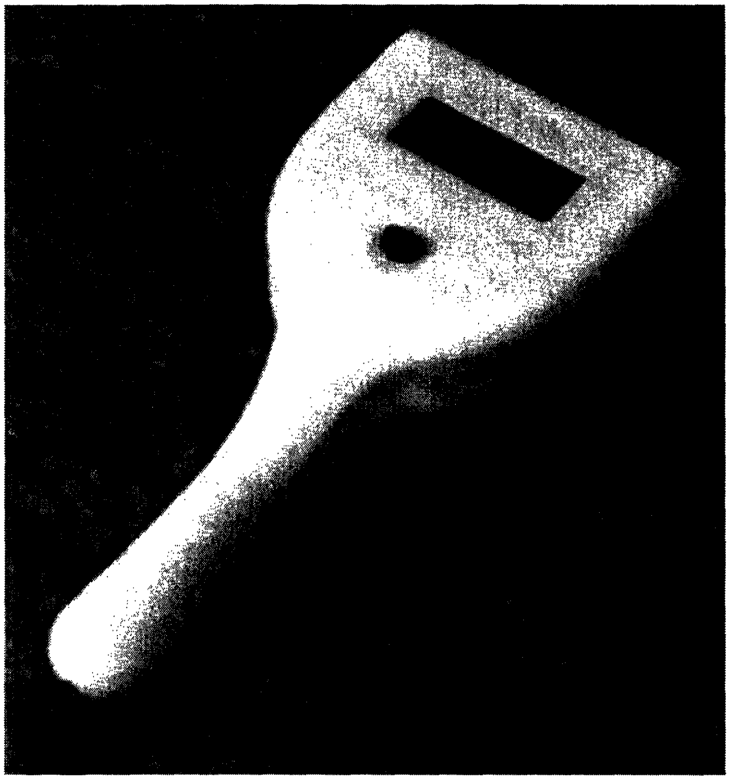


Figure 1: The user interface for the Active Joint Brace.

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[1] The Active Joint Brace is a powered orthosis which helps restore strength to the joints of its users by detecting the user's muscle contractions and then amplifying them by means of an external motor. Currently, it usage is aimed at restoring movement to the arms of stroke and spinal-cord-injury patients with some residual arm movement. Its use as a rehabilitation tool is also being investigated.

2.0 Data Interaction Interfaces

The very name "user interface" makes it clear that the purpose of this object is to allow the user to interact with the brace. More specifically, the UI allows the user to change a number of variables that affect the brace's usage. As will be further explained in **Section 3.0**, the UI is designed to be operated using only one hand; more specifically, only the thumb is used to actuate input devices. The specific interfaces for data interaction are specified below. Please refer to **Appendix A** for a detailed list of specifications for each part.

2.1 Display

The display is the UI's primary data output interface. The screen, or more correctly an LCD character display, serves as the display unit for the software controlling the functions of the brace. When a variable is changed in the software of the brace system the only visual feedback occurs on this display system. In order to access each of the user-modifiable variables, a multi-level menu system is used, which has multiple entries per sub-menu (see **Section 5.0** for information on the menu). Thus the screen used has the most vertical character lines available (four), in order to display as large a slice of the menu as . Beyond the purely functional requirements, it is also important to note that the LCD screen follows human factors. The Measure of Man and Woman[1] is a standard human factors reference, and its entry concerning dot-matrix read-outs corresponds to the characteristics of the UI's screen: the Lumex LCM-S01604DSF LCD Character Display[2], shown in **Figure 2**. This screen can display characters other than letters, numbers, and punctuation, which is useful for displaying nonverbal information such as thermometer bars[1] and check marks. The software user interface makes wide use of thermometer bars, using them both as indicators of user set variables, such as the screen contrast, as well as a form of biofeedback, changing a thermometer bar in proportion to the user's muscle contraction; additionally, check marks are used in many places on the menu to indicate the state of a toggle-able variable. In any event, due to the large amount of data that may need to be presented to the user, this relatively large display is a necessity.

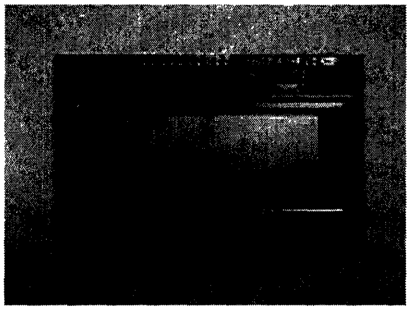

Figure 2: The Lumex LCM-S01604DSF LCD Character Display [2].

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[1] A thermometer bar is a solid line which increases in length proportionally to the change in some variable, in much the same way as a thermometer's liquid level rises in proportion to rising temperature

2.2 Navigation Switch

The UI's primary data input interface is a navigation switch. It allows for the selection of menu items and the incrementation of certain values, such as calibration numbers or the level of contrast in the LCD screen. Since the value change can be accomplished by the up/down movement of the switch, the selection function requires another mechanism, in this case a push button switch integral to the navigation switch. The particular navigation switch used in this application is the ITT/Cannon TPA311G Navigation Switch [3], shown in **Figure 3**, which meets most of the human factors considerations expressed in The Measure of Man [1] (see **Appendix A** for further explanation).

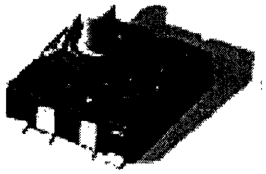

Figure 3: The ITT/Cannon TPA311G Navigation Switch [3].

The movement of the switch and its effects are intuitive: pushing up on the switch goes to the next highest menu item, or increments to a more positive value, while pulling down on the switch goes to the next lowest menu item, and increments a variable closer to zero. Furthermore, since the changes enacted by the switch are incremental, a method of feedback is needed to demonstrate to the user that a value has indeed been incremented. This is difficult here because of the architecture of the switch: the up and down movements do have detentes, however once the switch has been actuated it does not increment any value or switching mechanism, it just keeps the switch circuit closed. This is problematic because it is not advisable to require the user to have to push the button up, let it return to a neutral position, then press again, and continue this cycle in order to increment to desired value. Repetitive movements such as this lead to physical discomfort and absentmindedness, both of which should be avoided in a medical device. In this instance, to further increment values the user continues to press the switch in the desired direction, as is intuitive, and the software of the brace increments the value in question according to a set time step, that is, for every *n* time steps, the value is incremented *n* times. The problem of feedback is addressed by having a speaker which emits an audible click for every increment (the speaker is described in **Section 2.3**), as recommended by Tilley [1].

Because the navigation switch component only has a small protruding knob, a cover button has also been chosen, also produced by ITT/Cannon, part number BTNTPA90 [3], seen in **Figure 4**. The button is black, a neutral color, since it is used to perform many different, contrasting functions. Furthermore, since the knob itself gives no clue to its "push to select" usage, the casing above where it sits (see **Figure 1**) gives an indication about the possible movements of the button: the case there has a depression in the general shape of the knob, but longer than it is wide. The depth of the depression signals that the switch can be pressed downward, since the button is floating above the surface, while the elongation of the depression signals that the navigation switch accepts vertical movement, but not horizontal movement. The knob itself meets Tilley's specifications [1] for the size of a push button, which is the device it most closely resembles.

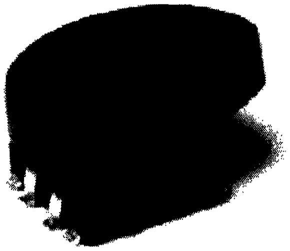

Figure 4: The ITT/Cannon TPA311G topped by the BTNTPA90 Cover Button [3].

2.3 Speaker

The speaker serves as a secondary output interface, allowing the device to have both audible and visual forms of output. It is used to provide auditory feedback (as explained in **Section 2.2**), and in the future may be used to provide biofeedback[1] as well. It is volume-controllable, since the level of background noise, as well as the sensitivity of the user's hearing, can change according the environment and the user. The volume, however, generally does not need to be modified quickly, and so the mechanism for change is contained in a software menu. The speaker can convey different tones, however it does not have great fidelity, since it is not needed, as the speaker is not reproducing music or speech. Thus, a compact and lightweight speaker, the CUI Inc. CEM-1206S Buzzer (**Figure 5**) [4], is used, in order to reduce the weight and size of the device. This device produces a maximum volume of 85 dB [4] at the opening, and so will not produce a volume over 80 dB (the level of a hair-dryer, described as annoyingly loud [1] according to the decibel chart) at the user's ear, due to the fact that the speaker is muffled by the enclosure, as well as the distance between the user's ear and the speaker. This keeps the volume level of speaker from annoying the people surrounding the user, even if the volume is set to maximum.

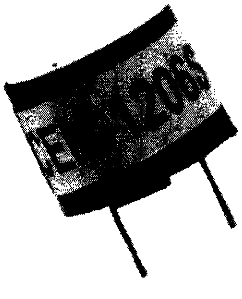

Figure 5: The CUI Inc. CEM-1206S Buzzer [4].

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[1] Pending further software revisions; the ability of the microprocessor to provide this feedback along with all of its current tasks may not be possible.

2.4 Hold Switch

There are some cases which it is helpful to disable the navigation switch, so that no accidental changes are made to the brace's function. This is the purpose of the hold switch: a toggle for the input interface. Since the hold switch allows for the impairment of normal operation, it is designed such that its status is intuitive and instantly recognizable. Part of this constraint is served by the switching mechanism: a slide switch that inherently displays its status by having the knob placed on one side or the other, depending on the active mode. To indicate the active state in this case, two methods are employed: first, when the controls are locked out, the base of the switch shows red instead of black, and second, the switch's hold position is on the left , and a lock icon is displayed on the enclosure to the left of the switch. So, when the switch is in the hold position the knob is next to the lock icon on the enclosure and the base of the switch shows red, while when the switch is in the normal operation mode the knob is away from the lock icon and the base shows black. The hold switch is the ITT/Cannon S102031SS03Q slide switch [5], **Figure 6**, which comes close[1] to meeting the human factors criteria in The Measure of Man and Woman [1]. Since this switch is not crucial to function, and, indeed, must be protected from accidental changes, instead of setting the knob 0.25" or more from the surface of the enclosure as suggested by Tilley[1] the face of the knob is flush with the enclosure. This requires the user to actively press against the fluted top-surface of the knob and slide the switch to the side in order to change its state.

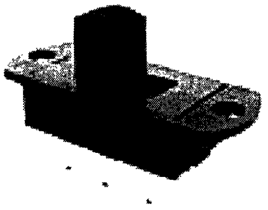

Figure 6: The ITT/Cannon S102031SS03Q Slide Switch [5].

2.5 Compact Flash Holder and Programming Port

While the Active Joint Brace is still being developed, there are a number of features the engineers on the project need implemented that will not be useful to the end user. Specifically, there needs to be a port available for reprogramming the microcontroller that is the brain of the UI, as well as a method for recording data on a Compact Flash card. These specific parts have been chosen by the engineer designing the circuit board which goes inside of the enclosure; however, because these parts must be accessed from time to time, they necessitate an opening in the enclosure, which is an issue for the design of the user interface. Since there must be an opening, this suggests a door mechanism, so that the delicate electronics are not normally open to the environment. The door mechanism will be discussed in **Section 3.2**.

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[1] No part could be found in the Digikey catalog[6] which exactly match the specifications in The Measure of Man and Woman [1]; this is the part closest to meeting those specifications. Note also that the switch does not come with a red/black base: the red side is painted on by hand using model airplane lacquer.

3.0 Enclosure

The interfaces specified in **Section 2.0** all need to be integrated into one device: that is the function of the enclosure, pictured in **Figure 1**, above. Since the brace is designed for patients lacking usable mobility in at least one arm, the controller is operable by one hand (as mentioned in **Section 2.0**). Furthermore, the controls are mounted such that they can be actuated by the user's thumb. This brings up a number of constraints. First, since the user only has one thumb per hand, all control actions must be accomplished by single actions (no simultaneous button pushing). This need fits well with a menu layout system, and the navigation switch specified in **Section 2.2**. Second, since the thumb is constrained to different directions depending on which hand is used to hold the interface, the UI aims to be operable by either hand. This is accomplished by having the navigation switch centered with its button located directly under the normal resting place of the thumb. The design is chiral, because the hold switch is located on the right side of the device, however, a left handed user can still reach the switch with his or her left thumb: it is just a more awkward movement to slide the switch.

3.1 Shell

The main body of the enclosure is split into two halves, the same way a clam shell is halved. Besides protecting the electronics inside, the top piece (**Figures 7** and **8**) serves to frame the LCD screen and has a hole to allow for the knob (**Figure 4**) on the exterior of the shell to connect to the navigation switch component (**Figure 3**), which is underneath the shell. The bottom part of the shell (**Figures 9** and **10**) serves primarily to support the printed circuit board. Additionally, both parts of the shell have notches for containing the hold switch (**Figure 6**), as seen on the left in **Figure 8** and on the right in **Figure 9**. Other prominent features include the hole at the base of the handle, where the wire exits the user interface to connect to the motor control box, the cut out in the back of both pieces where the door fits (see **Section 3.2**), and the posts in the back of each piece of the shell which serve as the axle support for the door. There are also many assembly features on the shell pieces, such as the labyrinth joint pieces that extrude from the bottom piece, and are accepted into slots in the top, and the screw post in the handle which holds the two halves together. The other important assembly feature is made up of the extrusions from the axle posts on the bottom piece, which fit into corresponding divots in the top shell; the mating of these features clamps the shell together in the vertical plane, while the labyrinth joints constrain the shells together in the horizontal plane.

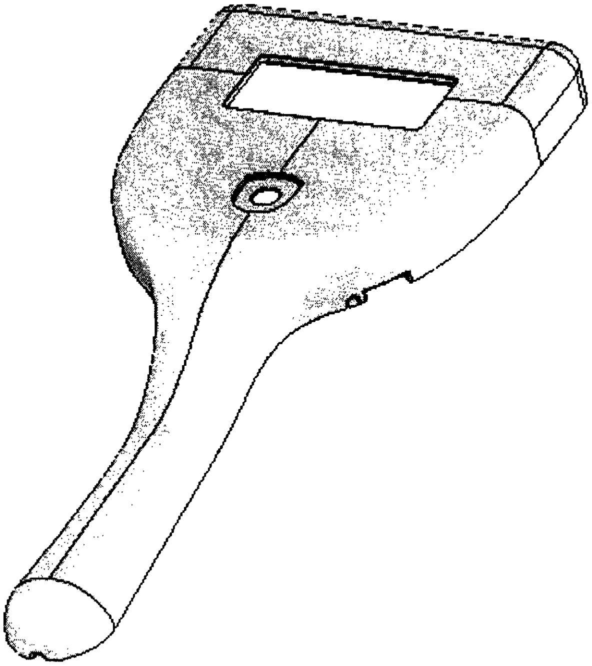

Figure 7: Top shell, top view.

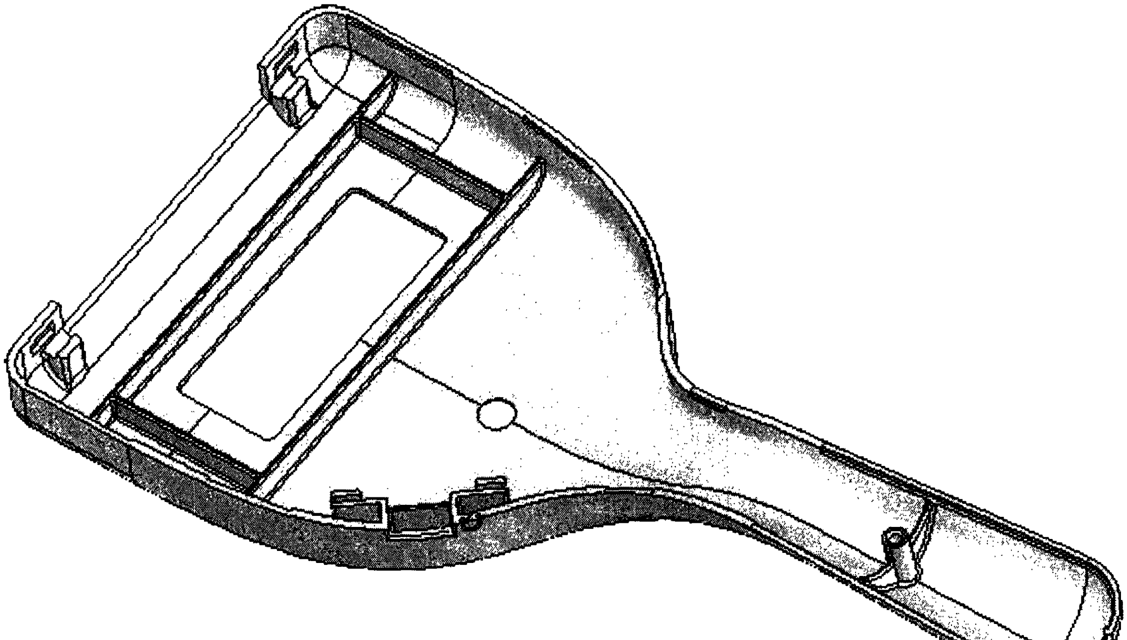

Figure 8: Top shell, bottom view.

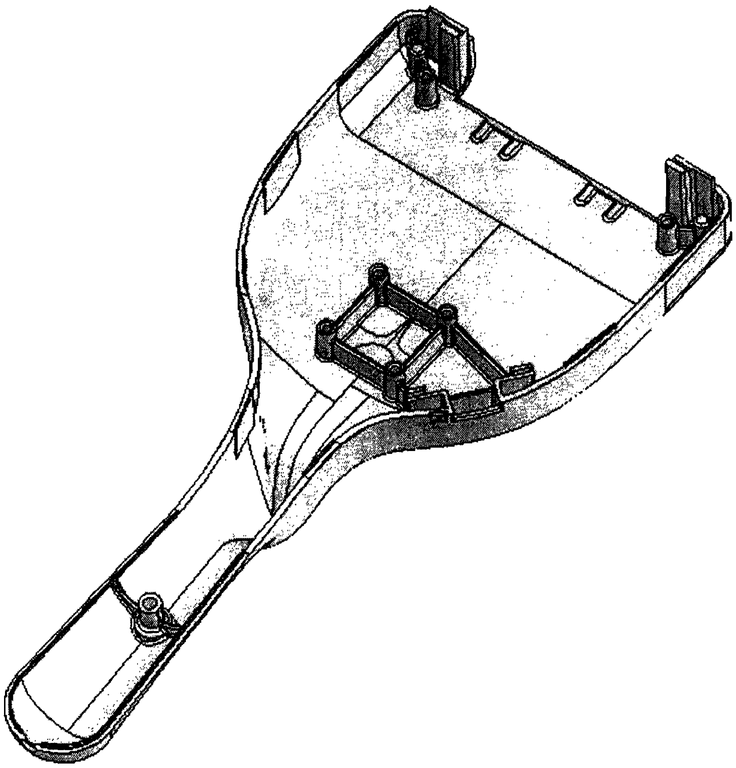

Figure 9: Bottom shell, top view.

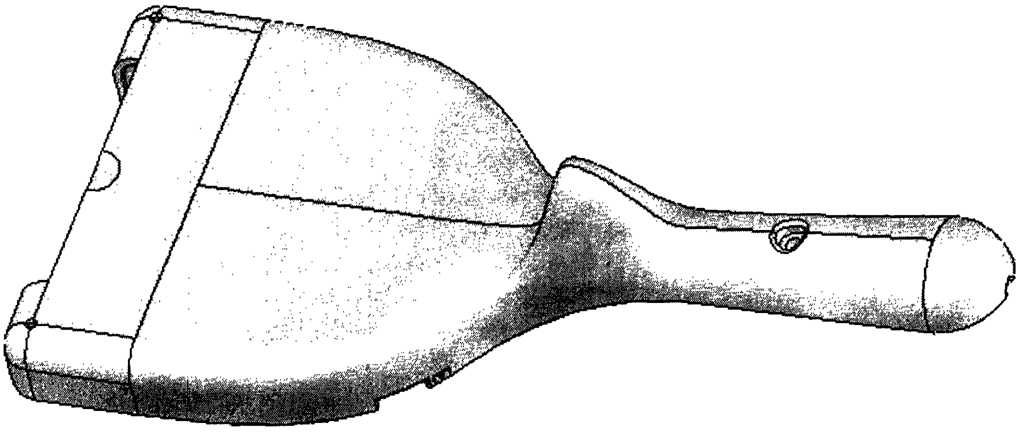

Figure 10: Bottom shell, bottom view.

Beyond the human factors which define its diameter (see the end of **Appendix A**), the handle contains two special features: the hump at the screen end, which the user hooks his/her index finger around to get a more secure grip, and the flared base, which prevents the handle from slipping out of the user's hand. It is necessary to assure the user in this way because without these features the UI would feel unstable due to the torque on the user's wrist, which is caused by the center of gravity of the device being about halfway between the navigation switch and the screen.

In order to have the enclosure ready to test as quickly as possible (and for as low a cost as possible), a rapid prototyping process was used to make a three dimensional, plastic version of the solid model. The prototype was constructed using Fuse Deposition Modeling, or FDM, which allowed for the use of a production material, ABS plastic (Acrylonitrile Butadiene Styrene), and thus the prototype looks and feels more like a finished product. Although the FDM process resulted in a surface finish which was not as smooth as injection molding, or even another 3D printing process such as stereo lithography, these surface imperfections can be smoothed with sandpaper, since the device is made of sandable ABS plastic. Even though the FDM'ed parts are not as smooth as they could be, their tolerances are done well enough that all of the important assembly features match up flawlessly. As seen in **Figure 1**, and below in **Figure 11**, the results of the FDM process closely matches the solid models.

Figure 11: The prototype UI

3.2 Door

As noted in **Section 2.5**, some of the electrical components contained in the enclosure, namely the compact flash card/holder and the programming port connection, need to be accessed from time to time. Therefore, there is an opening in the back of the enclosure, and it is covered by a door (the solid model of which is shown in **Figure 12**, along with a view of the door in an assembled solid model in **Figure 13**). To minimize the usage of fasteners, the door closes with a snap fit (**Appendix B** shows the calculations used to design the snap fit tab), and is hinged at the top, so that the door cannot be removed without disassembling the enclosure itself. In the real UI, the door does indeed close, however it requires a good deal of force, as predicted by the calculations in **Appendix B**. The door closes tight enough so that it does not open by itself or rattle excessively, and its fit is tight enough that it should restrict particles from entering the enclosure. However, the amount of force it takes to open seems excessive. In future revisions the snap fits will need to be reshaped.

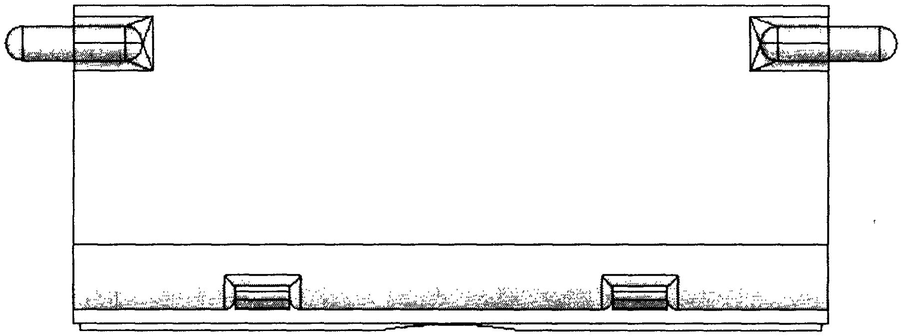

Figure 12: The solid model of the door piece, back view. Note the axles at the top and snap fit pieces at the bottom.

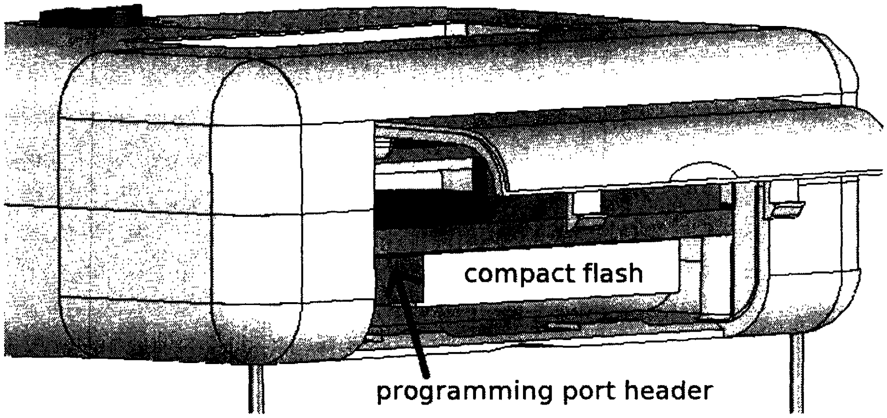

Figure 13: The door within a full solid model assembly of the UI, with the Compact Flash and programming port labeled.

3.3 Wire

As seen in **Figure 14** below, there is a bent steel wire inserted into the bottom piece of the enclosure. This wire ensures that the screen of the UI sits at a comfortable viewing angle (12° to be exact) [1]. Additionally, due to the curve in the wire, it can be used as a hook to hang the unit off of something, such as the arm of a wheelchair, or it can even be tucked into a person's belt (as seen in **Figure 15**). The wire is held in place by a press fit. Since the force applied to the wire acts either in the same direction as the press fit or normal to it in usage, this type of attachment is acceptable for a load-bearing device.

Figure 14: A right-side view of the solid model of the user interface. Note the wire on the right.

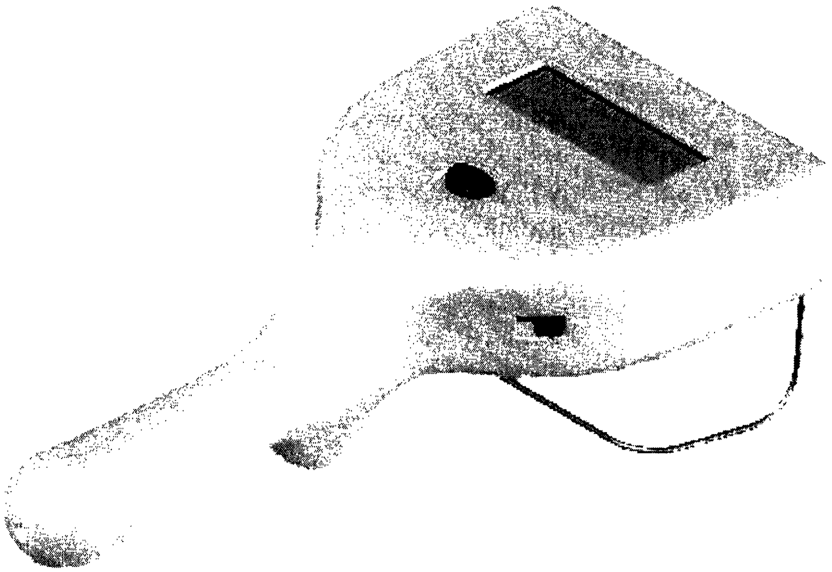

Figure 15: An isometric view of the solid model, better demonstrating the curvature of the wire.

4.0 Menu Layout

The menus the user must navigate in order to access and modify data must also be designed for ease-of-use. The menu items themselves are all predefined by the software of the brace, so the important design aspect is organizing the structure of the menu. The menu layout itself is listed in **Appendix C**. This organization was determined by conducting a survey of users who interacted with the first user interface, and using the replies from that survey to determine the contents of sub-menus as well as prioritizing the individual entries within each menu. For example, in the "Run" menu (the structure of which is reproduced below in **Note 1**[1]), "Halt" is the top menu item, since it may need to be selected in an emergency, "Gain" is second because it is the most commonly used item as well as being generally the first item used, "Display EMG" is used second most, etc. This menu layout is implemented in the software which is run by the electronics inside of the user interface's enclosure.

Note 1: The "Run" sub-menu from the Menu Layout Specification in **Appendix C**

- Run (not active until after Calibration; selecting this item puts the brace into run mode, and then brings up this menu)
    - Halt
        - [Exit run mode and go to top level]
    - Gain
        - [Set Gain]
    - Display EMG
        - [Display output of 3 filters – Emg1 / Emg2 / Emg3]
    - Smoothing
        - [Set Smoothing]
    - Max
        - [Set Max]
    - Virtual Spring
        - {Toggle virtual spring on or off, display check mark for "on"}
    - Virtual K (only if virtual spring is toggled on)
        - [Set K of virtual spring]

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[1] See **Appendix C** for the full Menu Layout Specification, along with a legend explaining the usage of square braces versus curly braces

5.0 Conclusion

The Active Joint Brace is a powered orthosis: a wearable device meant to aid the user's movement by assisting, or, in some possible therapeutic cases, resisting, the user's muscle function. Since this device's user may be handicapped, it is crucial that the interface to its user controls be intuitive and simple, along with ergonomic. By defining the interface between the user and data, the device which enclosed these interfaces, and then the construct which allowed the user to manipulate data, a user interface was designed for the Active Joint Brace, and is now ready for deployment alongside the brace in clinical trials.

From the evaluations conducted on the UI, a number of improvements and fixes have been outlined. First, the knob feels to be a half inch or so too high, and so in future revisions it will need to be placed lower. Second, the index finger hump has a bit to orthogonal of an angle on the screen side, and should be more rounded, and perhaps smaller, to be more comfortable for users with smaller hands. The menu layout specified in **Section 4.0** was defined with input from the current pool of users of the brace's interface, of which there are only five. As this pool increases, more surveys should be taken in order to either confirm the order outlined here or outline the changes needed in the next revision. In addition to the user interface, the motor housing of the brace could also use a new design, and since they are both a part of the same device, care should be taken that the two designs have a similar aesthetic. All in all, though, the form and function of this user interface have been validated, and it will undoubtedly be assisting in clinical trials soon, and possibly further as the brace continues development.

Acknowledgments

The author would like to thank Kailas Narendran and John McBean for their work on the Active Joint Brace, supervised by Prof. Woodie Flowers: without the brace, there would be no need for a user interface. Furthermore, it was Prof. Flowers' opinion of the previous, off-the-shelf plastic box user interface that got the user interface project started. It was in a meeting attended by the author, Prof. Flowers, and Messrs. Narendran and McBean that the original sketches for the UI were born, and its overall shape was inherited from those sketches. Messrs. Narendran and McBean and Prof. Flowers were also helpful in assisting the author with several small problems in the design of the enclosure. Specifically, the labyrinth seal was suggested by Mr. McBean, Mr. Narendran suggested that the LCD display be sunken below the surface of the enclosure, and Prof. Flowers suggested the flaring of the handle. Messrs. Narendran and McBean, along with Kate Zebrose, also of the Active Joint Brace group, participated in periodic design reviews which helped to iron out the design.

The author would also like to thank Mrs. Zebrose for her work in designing the electronic hardware that goes inside of the enclosure and which supports the electronic parts specified in this paper. Mrs. Zebrose and Mr. Narendran are also responsible for writing the software which runs the brace, upon which the author imposed the menu specification. Finally, the author would like to thank Mike Littrell at C.ideas Inc. for his help in setting up the rapid-prototyping of the enclosure.

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Appendix A: Parts Specifications

The parts below were selected according to the criteria set out in **Section 2**.

All of the dimensional specifications come from The Measure of Man and Woman[1]. Items in *italics* fail a specification.

Display

Selection criteria:

- 4+ lines of vertical lines of text.
- 0.2" - 0.67" tall character height.
- 5x7 dot matrix, 7x9 for lowercase letters.
- Non-alphanumeric characters can be displayed, possibly even graphics.

A part that meets most of these criteria is the Lumex LCM-S01604DSF LCD character display **(Fig. 2)**:

- 16 character, 4 line display.
- 0.18" character height (this is the standard for character displays; it fails the specification, but no parts exist that meet all of the specifications).
- 5x8 dot matrix (so no lowercase).
- Non-alphanumerics can be displayed, graphics possible, but they are crude, and require additional programming.

Navigation Switch

Switch selection criteria:

- Switch has detentes, or other feedback.
- Switch has three actions: up, down, and select.
- 10-20 ounces select button resistance.
- 0.09-0.25" travel.

A part that meets most of these criteria is the ITT/Cannon TPA311G navigation switch **(Fig. 3)**:

- The switch has no detentes, since it only goes up and down: the buzzer will be used to make a click noise for feedback when changing menu items.
- Switch has three actions: up, down, select.
- 14 ounces select button resistance.
- *0.01" travel*; this is the only available up/down/select switch in the Digikey catalog[6], so this must be tolerated.

Button cover selection criteria:

- 0.5 - 1" Diameter.
- Neutral Color.

A part that meets these criteria ITT/Cannon BTNTPA90 button cover(**Fig. 4**):

- 0.5" Diameter average.
- Black Color.

Speaker

Selection criteria:

- Maximum volume below or limited to 80 dB.
- Compact, lightweight.
- Optimally runs on 5V DC.

A part that meets these criteria is the CUI Inc. CEM-1206S buzzer (**Fig. 5**):

- Maximum volume 85 dB, can be software limited; also limited by the case itself.
- Compact, lightweight (0.47" diameter, 0.35" tall).
- Rated at 5.0 V, operates between 3 and 8 V DC.

Hold Switch

Slide switch selection criteria:

- Knob dimensions: 0.25 – 0.75+" long.
  0.25 – 1" wide.
- 10 – 16 oz. of resistance.
- Integral state notification (red on one side, black on the other, etc.).

A part that meets most of these criteria is the ITT/Cannon S102031SS03Q slide switch (**Fig. 6**):

- Knob dimensions: 0.28" long.
  0.22" wide.
- Button resistance numbers not available; estimated at around 16 ounces.
- State notification (red or orange paint) will be added by hand, since it is not available in the stock part.

This switch does not meet all specifications, but it is the closest commercially available part to the specification.

Enclosure

Specifications:

- Handle has circular cross section.
- Handle grip diameter: 0.875 – 1.25".
- Handle length > 3.9".
- Navigation switch 1.7-2.7" from the crotch of the thumb (e.g. the screen end of the handle).
- A way to access the Compact Flash card and programming port.
- The screen is easily viewable while the UI is resting on a table.

As designed, the part has these features:

- Handle has circular cross section.
- Handle grip diameter flares from 1.2" at the base to 1" at the screen end.
- Handle length ~ 5" (depending on where it's decided the handle "stops").
- Navigation switch 2" from center of handle at the index-finger-hump, 0.5" from where the crotch of the thumb falls on most users who hold the UI.
- There is a door in the back of the UI, under which is the compact flash card and the programming port.
- The bent wire holds up the back of the UI so that the screen is tilted to 12°.

Appendix B: Snap Fit Calculations

The snap fit used in the door is governed by an equation based of the cantilever beam bending equation [7]:

$$y = \frac{2\epsilon l^2}{3h} , \tag{1}$$

where, as seen in **Figure 16**, y is the maximum deflection, l length of the undercut, h thickness of the beam at the undercut, and ε is the permissible strain. **Figure 17** shows the relevant dimensions for the door, and the Dow Chemical Company [7] gives the one-time permissible strain for ABS to be 1.4, with a recommendation that, for repeated loading, permissible strain be set at 60% of one time, in this case, 0.84. Inserting these numbers into Eq. (1):

$$\frac{2x0.84x(0.120in)^2}{3x0.040in} = y = 0.202in , \tag{2}$$

so, the maximum permissible deflection is 0.202", which is more than enough for the snap fit designed, which requires a deflection of only 0.025" as seen in **Figures 18** and **19**. There are a number of reasons for this large of a difference. First, even though the door is made of ABS, it is ABS formed by FDM, not injection molding, and therefore the material only has 60-80% of the strength of injection-molded ABS, which could therefore lower the permissible deflection down to 0.121 in the worst case. Also, since rapid prototyped parts have a much less homogeneous consistency than injection molded parts, it is advisable to have a very large safety factor, in this case, around six. Having such a large margin also allows the snap-fit to have a lower assembly force. Most importantly, however, is the fact that the snap fit rotates into place, and thus out of place, and without the smaller gap the removal force of the snap fit would be too high.

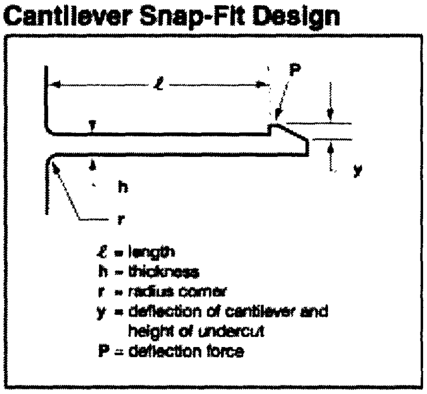

Figure 16: Diagram describing variable names [7].

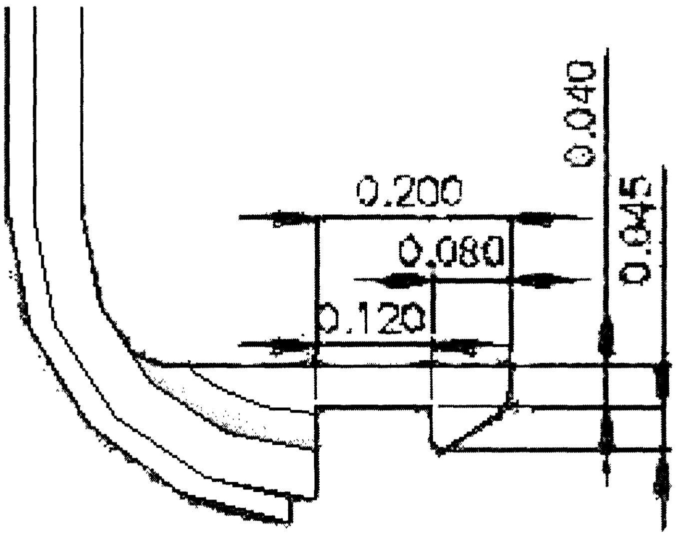

Figure 17: Dimensioned sketch of the door's snap fit.

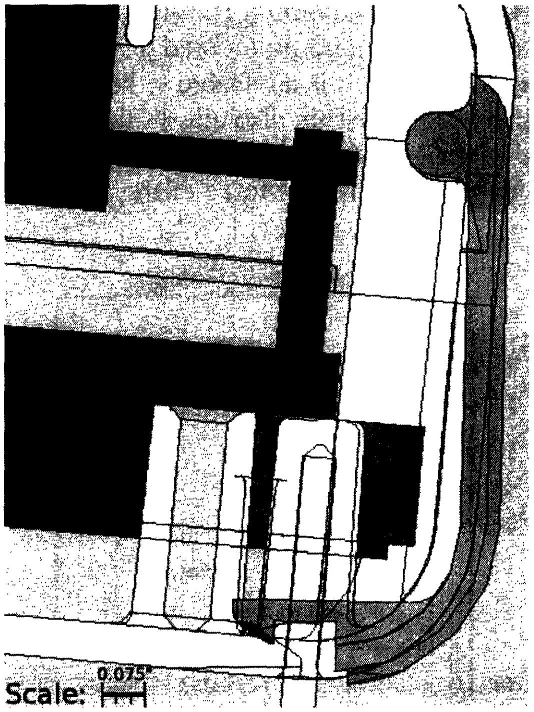

Figure 18: Wire-frame view of the solid model assembly, enclosure shown in white and door in grey. Note the scale, which shows the interference, the dark grey intersection between the door and enclosure, here at around 0.025"; additionally, the height of the pocket the tab snaps into is exactly 0.025".

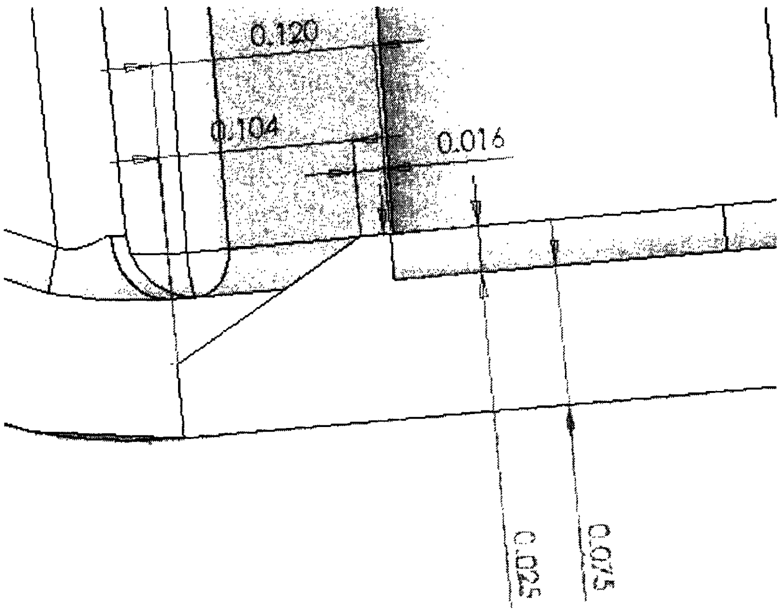

Figure 19: A cross section of the bottom shell piece, showing the relevant dimensions of the pocket which accepts the door's snap fit.

To find the theoretical assembly force, we back solve Eq. (1) for the strain, ε:

$$\epsilon=\frac{3\,yh}{2l^2}\ . \tag{3}$$

Now, by plugging in the design value for *y* into Eq. (3), the theoretical strain can be found:

$$\frac{3\,x\,0.025\,in\,x\,0.040\,in}{2\,x\,(0.120\,in)^2}=\epsilon=0.104\ . \tag{4}$$

This strain, along with the secant (or flexural) modulus, *E*, the thickness of the tab *b*, the thickness at the undercut h, and the length of the tab *l*, can be used to find the theoretical deflection force, *P* [7]:

$$P=\frac{b\,h^2\,E\,\epsilon}{6\,l}\ . \tag{5}$$

The makers of the ABS used in the FDM machine give its flexural modulus as 176000 psi [8], so inserting the numbers into Eq. (5):

$$\frac{0.200\,in\,x\,(0.040\,in)^2\,x\,176000\,psi\,x\,0.104}{6\,x\,0.120\,in}=P=8.14\,lbf\ . \tag{6}$$

The insertion force *W* is determined by this deflection force (*P*), coefficient of friction *μ*, and angle of incidence α [7]:

$$W = P\left[\frac{\mu + \tan\alpha}{1 - \mu\tan\alpha}\right] \quad . \tag{7}$$

The Dow website estimates that the coefficient of friction between two ABS surfaces is maximally 0.72 [7]. Due to the geometry of the snap fit in this case, a problem arises concerning the angle of incidence α: since the door rotates into place, the angle of incidence changes from 0° (that is, the tab and the piece it rubs against on the enclosure are parallel), to 30° or so. So, to find a maximum value, assume an α value of 30°:

$$8.14\,lbf\left[\frac{0.72 + \tan 30^o}{1 - 0.72\tan 30^o}\right] = W = 18.1\,lbf \quad . \tag{8}$$

This maximum value is within the amount of force a human in the fifth percentile can exert with their hand (40 lbf) [1]. Even though this is a good deal of force, it must be noted again that this is the maximum value possible.

Although no measurements have been taken, the closing force in the model feels much more like 1.81 lbf than 18.1 lbf. The issues with the angle of incidence above, along with manufacturing inaccuracy in the FDM probably contributed to this deviation. It must be noted, however, that as parts begin being produced by means other than FDM the design of the snap fit will likely need to be changed, since the flexural modulus and allowable strain will both change with the material.

Appendix C: Menu Layout Specification

Legend:
[Action leads to new screen]
{Action changes an on screen value, or does something in the background}
The top menu item in each section is pre-selected.
Before the menu is displayed, a warning is shown to ensure the user is using the correct arm.

Normal Operation

- AutoCalibrate
    - [Run the auto-calibration function, then display values for each of the sensors on one screen]
        - [Run]
        - {Change value for Emg1 / Emg2 / Emg3}
- Run (not active until after Calibration; selecting this item puts the brace into run mode, and then brings up this menu)
    - Halt
        - [Exit run mode and go to top level]
    - Gain
        - [Set Gain]
    - Display EMG
        - [Display output of 3 filters – Emg1 / Emg2 / Emg3]
    - Smoothing
        - [Set Smoothing]
    - Max
        - [Set Max]
    - Virtual Spring
        - {Toggle virtual spring on or off, display check mark for "on"}
    - Virtual K (only if virtual spring is toggled on)
        - [Set K of virtual spring]
- Settings
    - Backlight
        - {Toggle backlight; display check mark for "on"}
    - Muscle Group
        - {Toggle between Biceps and Triceps, make the setting apparent, e.g. display [Bi] or [Tri] next to the menu entry }
    - Contrast
        - [Set Contrast]
    - Volume
        - [Set Volume]
    - Clicker
        - {Toggle the click for each menu change; display check mark for "on"}
    - About…
        - [Go to About screen, show software revision]
- Standby

Debug Mode

This sub-menu is added between the “Settings” sub-menu and the “Standby” item on the top level:

- Debug
    - ☐ ZeroG
        - [ZeroG Mode]
    - ☐ Jog
        - [Jog Motor]

Beyond these layouts, for each menu item with an [action], except for the “Run” menu, there is a “Back” menu item at the bottom of each menu to return to the previous menu.