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The WPI Space Glove Design Project

abstract

WPI was one of four colleges and universities awarded NASA grants for student design and development of an improved glove for space suits. This paper traces the design, development and testing of the WPI prototype glove. Test results showed that the glove did not significantly limit hand and finger motion when pressurized at 8 psi, except in the spherical grip mode. This project demonstrated that problems originating from space technology provide excellent vehicles for student learning and can generate creative solutions.

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INTRODUCTION

Man's interactions with the space environment have increased tremendously since the Space Transportation System became operational. Significant extra-vehicular activity by shuttle crew-members is required to fulfill mission, payload, and contingency requirements. Before leaving the pressurized environment of the shuttle, crew-members must don space suits and life support systems to survive in the space environment.

Space suits are currently pressurized to 4.3 psid (psi differential). There are various scenarios for acclimating astronauts to the current suit pressure, but all involve lengthy procedures to prevent decompression sickness. In one common scenario, if the cabin pressure is 14.7 psid the astronauts must prebreathe pure oxygen to flush the body of inert gasses for 220 minutes and still run the risk of decompression sickness. Another method involves lowering the cabin pressure to 10.2 psid for 3 days before partaking in EVA (1).

With an 8 psi suit, a cabin pressure of 14.7 psid could be maintained and no prebreathing or delay time would be required. NASA has a prototype hardsuit that can support an internal pressure of 8 psid, but the gloves for this suit perform poorly at 8 psid. This project addressed the need for an 8 psi space suit glove with maximum flexibility and durability which can be integrated as the final part of the prototype 8 psid space suit (2).

The American Society for Engineering Education (ASEE) administered a NASA contract to sponsor a glove design competition among engineering colleges. The four final contestants were selected on the basis of proposals submitted to ASEE. Each final contestant received a project grant of approximately $30,000.

WPI, as one of the four final contestants in the NASA/ASEE Glove Design Contest, utilized the undergraduate Major Qualifying Project (MQP) as the vehicle

to design the WPI entry. The MQP is one of four degree requirements at WPI and, as such, requires essentially 1/3 of a student's entire effort during the senior year. The MQP group consisted of 11 students from several Mechanical Engineering sub-disciplines. Several faculty served as advisors and 10 additional students participated in generating glove concepts via a campus wide concept competition. This paper describes the development, testing and evaluation of the WPI prototype design.

DESIGN REQUIREMENTS

The ideal space suit glove would provide unrestricted hand motion and minimize the work required to flex the glove. The glove would be comfortable to wear and provide tactility comparable to the hand alone. These design goals will probably never be fully attained since the pressure internal to the glove tends to stiffen it and causes it to resist bending. In addition, design measures taken to contain the pressure loading tend to influence the range of motion, comfort, and tactility.

Some aspects of the current shuttle glove, which operates at 4.3 psid, can also be used in designing an 8.0 psid glove. Adequate wrist designs for connecting the glove to the space suit are currently available. The current TMG garment which fits over the glove to provide thermal and micrometeorite protection is adequate. The current bladder is also acceptable.

The major problem faced in space suit glove design is that the hand is a complex anatomic structure with very complex kinematic motions. There are six types of grasping patterns Figure 1 (3). From a kinematic standpoint these grasps are achieved by motion about virtual centers which are internal to the hand and in many instances traverse a three-dimensional path in space. Any structural components or exoskeleton incorporated into the glove to provide for containment of the pressure loading must attempt to maintain the integrity of rotation about these natural virtual centers. Failure to do this will result in restriction of motion and/or considerable discomfort (point loading, chafing and abrasion).

Specific design requirements stated that a person wearing the glove be capable of grasping a 1-1/2 inch diameter cylinder. The WPI student team felt that a glove which simply achieved this minimum requirement would not be satisfactory and therefore set as a goal producing a glove that would function acceptably in all six grasping patterns. The WPI design group focused their efforts on four major areas; fingers, thumb, palm and metacarpal joint (Figure 2).

Although there were many issues which could have been given high priority such as manufacturability, sizing, tactility etc., it was determined that the fundamental problem was that of functionality. It may little sense to the student group to address issues other than those associated with achieving a combination of concepts which would yield a glove that worked at 8 psid. These other issues were viewed as second generation problems once the fundamental problem of functionality had been solved.

METHODS

A design team composed of students with major interests in mechanical design, materials and manufacturing, and biomedical engineering was assembled. Each of the eleven students spent approximately 1/3 of an academic year working on the glove design as a Major Qualifying Project (MQP) which is a WPI degree requirement. A multi-disciplined group of faculty advisors worked with the students

during the entire academic year. Ideas for the design came from two sources: the project students themselves and a campus-wide student competition.

For the campus-wide competition, summary information regarding specification, environment, and history was distributed to potential contestants, and two briefing sessions were held to discuss the issues associated with glove design. The competition solicited design concepts for either an entire space glove or parts thereof, and was open to the entire student body. The competition was open for three weeks at which time written or physical entries were received. The campus-wide design competition involved many students not directly associated with the design team and generated some innovative concepts. Members of the student design team generated ideas individually and also by participating as a group in a synectics problem-solving session that was led by a facilitator from a local industry.

The design team developed a decision matrix using the methods suggested by Dieter (4) to evaluate all of the concepts. As design concepts evolved into hardware, prototype gloves were built and tested at 8 psid in a glove box. A series of glove evaluation procedures were developed to test the kinematic capabilities of the prototypes. Redesign eliminated many problems present in the early prototypes.

RESULTS

Evolution of Design

The bases of the WPI design evolution were the design concepts which resulted from the design contest and subsequent activity. Nine contest entries were received. Two additional concepts were generated from the synectic brainstorming session. All eleven concepts and the present NASA shuttle glove were evaluated using the evaluation criteria developed by the project group and assigned values of relative acceptabilities. The decision matrix criteria are presented in Table I. For reference the relative acceptability of the current NASA shuttle glove was rated at about 42% by two faculty members who had worn one at 4.3 psid.

Some of the concepts generated by the design competition and the MQP students themselves involved:

1. An almost rigid glove except in the joint regions of the fingers, thumb and metacarpal. The finger sections were connected along the neutral bending axes.

2. Elimination of the palm bulge problem using a shell constructed of small triangular plates to create bending along the natural creases of the hand. The plates were bonded to a flexible material to create hinges and were bevelled to limit bulging of the shell. Thus the plates could bend with the palm but not bulge under the pressure load.

3. The use of elastic straps in combination with rolling or toroidal convolutes. The straps exerted a restoring force on the convolutes to assist them in returning to their neutral position. The elastomer was placed over the pressure retention bladder to help cancel the elastic and pressure loads.

A combination of the above 3 concepts had a relative acceptability of 79%. Due to this very favorable rating these concepts were studied and developed further.

It was recognized, early, that there were several fundamental issues to be addressed. Among these were the palm bulge, metacarpal joint, and thumb joint areas. Several difficult problems had already been solved by NASA including wrist, universal bladder, and TMG garment which would be retained in the WPI prototype.

Pursuit of an improved glove design based on these selected concepts included developments in four basic regions: fingers, palm, thumb, and metacarpal. The evolution of each component is briefly traced in the following paragraphs.

Fingers. The finger evolutionary tree, Figure 3a, shows two basic branches corresponding to hard and soft finger elements. The hard finger concept utilized base fabric covered with tubular elements connected with flexible elements along the neutral axis. It was found that each hard element had to be individually sized and would have been much too tedious and expensive to produce in practice. The soft finger element concept is very similar to that used in the restraint garment of the present shuttle glove. Both rolling and toroidal convolute joints were investigated with and without neutral axis restraint lines. It was found that restraint lines were necessary for load control and, in addition, provided adjustability for sizing. Rolling convolutes on the dorsal side with neutral axis restraint lines proved sufficient to allow extension during finger motion.

Palm. Three different palm concepts were initially investigated, Figure 3b. First, a soft palm similar to that of the present shuttle glove was tested. It was soon found that palm bulge could only be prevented using some type of exterior structure to force a concave shape.

The second branch began with a discrete shell structure made of small, stiff triangular elements fused to a flexible cloth backing. This made a material capable of bending in one direction but rigid in the other. This structure could bend along any of three axes, but only along one at a time.

The third approach utilized three rigid palm pieces connected by flexible elements of fabric. It was found that there existed a triangular area in the palm that moved very little relative to the dorsal side and that there was a connecting path between the thumb and first finger which similarly had little relative motion. The Type I palm clip, Figure 4a, was designed to take advantage of the lack of relative motion and to transmit the pressure load of the palm to the dorsal side of the hand where it could be pressure balanced.

Upon development of the palm clip for the lower palm, the discrete shell element evolved into a "sheet hinge" palm consisting of straight bars parallel to the metacarpal bending axis and covering only that region. The hinge was designed to bend in the concave direction: that is, it could not flatten. The sheet hinge concept and the Type I clip were combined to form the "combination" palm bar. Although the hinge could only bend one direction, interfacing it to the dorsal metacarpal region proved very difficult so that this approach was abandoned. This interface problem and concurrent evolution of design concepts in the metacarpal area led to the Type II palm bar, Figure 4b, which was essentially a Type I palm bar with a loop running around the hand. The loop ran along a connecting path between the thumb and first finger which had little motion relative to the Type I palm clip. With refinements the Type II palm bar evolved into the shape used in the WPI prototype design.

Metacarpal Joint. The metacarpal joint component began from three basic branches, Figure 3c. The simplest solution was an entirely fabric metacarpal joint employing convolutes on the back of the hand. While this branch was unsuccessful by

itself, due to bulging, it did provide the basis for several designs in the other two branches.

The second branch design employed elastomers to restrain the metacarpal. The neutral axis (NA) lines of the fingers were attached to elastic strips across the convolutes on the dorsal side. This led to a design with the entire dorsal surface of the glove made of an elastic material. Both of these designs, though, proved incompatable with the Type II palm clip. An attempt was made to employ elastic to take the load from the NA restraint lines from the fingers to the wrist, but the spring constant of the elastic proved too critical to this design.

The final branch consisted of exoskeletal design solutions involving various mechanical hinges. Hinge concepts were abandoned because the center of rotation of the metacarpal joint is inside the hand and inaccessible. In an attempt to create a kinematically equivalent motion a "traveler" was employed which consisted of a small pulley riding on a loop between the fingers. The loop was arranged so that NA lines from the fingers were always radial to the axis of the metacarpal joint. Due to concerns over friction and wear, the traveler was abandoned in favor of high-strength cords or "yokes" running through the crotch of the fingers. As the NA lines were fixed to the yokes, the yokes would not allow extension when the metacarpal joint was flexed, so this design was discarded.

Another line of development began with a 4-bar linkage originally proposed as a finger joint in the design competition. Each joint consisted of two rings placed around the fingers crossed proximal and distal to the joint line. The rings were semi-rigid while the rockers were flexible cords. It was realized that two loops around the hand would be hard to employ, therefore, a much simpler solution of attaching the finger NA restraint lines to a single loop at the base of the fingers and restraining this loop with NA lines along the sides of the hand was employed. With refinements in shape this "metacarpal restraint bar" (MRB) became part of the WPI design, as shown in Figure 5.

Thumb. The thumb design evolved from two branches (hard and soft) similar to the finger design, Figure 3d. Concepts concurrently developed in finger and metacarpal areas were combined in the thumb area. The upper thumb used a design similar to the fingers. Two saddle-shaped loops were joined and used to restrain the lower thumb. NA restraint lines from the upper thumb were attached to the upper loop, and the lower loop was attached to the wrist and palm bar by NA lines.

Another design consisted of just a restraint loop attached to NA lines leading to the palm clip and wrist. This design and the saddle-shaped loop concept were combined and modified, resulting in one loop along non-extension lines in the palm and another loop at the base of the thumb digit. NA lines were run from the wrist and palm clip to the first loop and from there to the second loop. NA lines on the thumb digit were attached to the second loop.

The WPI Prototype Design The WPI prototype glove was the result of integrating ideas developed from these concepts, as shown in Figures 5, and 6. The Type II palm clip was used to control palm bulge and to serve as a base of attachment for other components. The fingers, metacarpal, and thumb all used designs based on force transmission through the neutral bending axes. In each case the pressure loading was supported either in the direction of zero bending or along lines of non-extension neutral axes.

For the fingers, the radial pressure loading, hoop stress, was supported by the restraint garment fabric. The axial pressure load was supported by restraint

lines running down the sides of the fingers along the neutral bending surface, a plane of non-extension. To ensure that the axial loading was not supported by the glove fabric, the restraining garment fingers were designed overly long so that the restraint lines, when adjusted, would be shorter than the garment finger length. The restraint lines were fixed at one end to the glove fingercaps while the other end could be adjusted at the attachment to the metacarpal restraint bar (MRB). Pleating on the dorsal side allowed for an increase in length during bending. Under the pressure loading, axial loads were supported by the restraint lines while radial loads were supported by the fabric which functioned as hoops around the finger. With these dorsal pleats, the finger joints were functionally equivalent to a rolling convolute.

The metacarpal flexure design employed the same operating principles as that used in the finger joints. Since the cross-section of the metacarpal region is non-circular, the fabric itself could not be used to contain the radial pressure loads. The MRB, a continuous oval-shaped loop of rigid material was attached to the glove fabric just above the knuckles. Non-extension lines connected the MCB to the Type II palm clip and thus supported the axial loads through the metacarpal hinge axis. An elliptical convolute in the fabric was designed to allow extension of the metacarpal dorsal area. Some difficulties were experienced since the convolute tended to bulge outward, indicating that possibly an additional restraint in the form of a rigid hoop or palm clip extension would be required. Such a structure was not implemented on the WPI prototype. Functionally, the joint worked satisfactorily but required expenditure of flow work. As in the fingers, the metacarpal fabric was overly long to ensure that the restraint lines would carry the axial loading rather than the glove fabric.

The thumb of the restraint garment was designed using concepts similar to those used in the fingers and metacarpal regions. Two rigid loops were used to attach restraint lines in the thumb area. The thumb base restraint loop was affixed to the glove fabric at the base of the thumb. The secondary thumb loop was attached to the glove fabric above the second joint. Restraint lines were attached between the two loops along non-extension lines to support the axial pressure load. As with the fingers and metacarpal, a combination of the dorsal convolutes and excess length ensured the loading was taken by the restraint lines rather than the glove fabric. Radial loading was supported by the glove fabric, and by the restraint loops in the lower thumb region.

The Type II palm clip was the final element of the WPI design. It was installed so that the triangular section covered the region of negligible deformation on the palm. The rigid palm clip served to balance the pressure load over the palm and dorsal side of the hand and eliminate palm bulge. Both the palm clip and the thumb base restraint loop were terminal points for the neutral axis restraint line system. Between these pieces and the wrist the glove fabric assumed all loading. In this way loading was evenly distributed into the sleeve. Little flexibility was lost since bending was not required in the areas distal to the wrist, where the fabric was load bearing. As noted earlier, the existing NASA wrist joint provides a near optimum solution for that region.

Test Procedures and Results for the WPI Prototype Design

As many of the standard glove tests were developed to prove safety, the WPI design team created several non-standard tests to evaluate the functioning of the prototype gloves. Even though the tests were of a somewhat qualitative nature, they did evaluate the kinematic capabilities of a particular design. In general, the test sequence was designed to compare the motion of the hand in its natural

state to the motion of the hand while in the glove at 8 psid. The tests used and the results for the final WPI prototype follow:

1. Cylindrical Grip Test

Dowels from 1/4 to 3 inches in 1/4 inch steps were successfully grasped in the cylindrical grip mode with the glove under pressure.

2. Grip Modes

All 6 basic grips are executed as shown in Figure 1. Each grip is rated on a scale of 1/poor to 5/excellent.

	Poor			Good	
Tip	1	2	3	4	5
Palmar	1	2	3	4	5
Cylindrical	1	2	3	4	5
Spherical	1	2	3	4	5
Hook	1	2	3	4	5
Lateral	1	2	3	4	5
Average			3.5		
Average w/o Spherical					4.0

3. Individual Finger Motion

Using a flat board with a slot cut for one finger, each finger was bent through the slot while keeping the rest of the hand flat and the range of movement was recorded. The performance of the hand with the glove unpressurized and of the hand with the glove pressurized to 8 psid were compared with the full range motion of the hand without a glove.

Finger	% of full range motion	
	glove w/o pressure	glove with pressure
Index	97	88
Middle	82	72
Ring	77	67
Little	94	68
Avg. of 4 digits	87	74
Thumb	95	19

4. Comfort

The subject for whom the glove had been fitted wore the glove for 1/2 hour under pressure while executing basic movements. The subject's hand was examined for bruising, chafing and avulsions. The glove caused minor swelling of the knuckles and some chafing. Much of the swelling was caused by point loads on the hand. The subject rated the comfort of the glove as only fair.

Test Conclusions

The cylindrical grip range of 0.25 to 3.0 inches diameter should be more than adequate for any task requiring this grip. This large range of mobility was directly attributable to the ease of metacarpal motion as a consequence of the MRB and finger designs. These same factors provided for good results in the grip modes. The spherical grip was limited by low range of thumb motion and minor

interference from the palm clip. As the spherical grip is not used as often as the other grips, this should not prove to be a major problem.

Individual fingers were able to move in excess of 65% of their full range while under pressure. The index finger achieved 88% of its full range motion which accounts for the good results in the grip modes tests. The thumb motion although rather limited, nevertheless covered the midrange used for most applications. The glove functions over a substantial range of useful work modes and retains tactility comparable to the current shuttle glove. The limited thumb motion was largely due to a small allowance for extension in the dorsal side of the restraint garment.

No attempt was made to address the comfort issue. Current means of increasing comfort could eliminate much of this problem. Flocking inside the glove bladder would be one major improvement. Padding inside the restraint garment or palm clip could distribute the point loads and greatly increase the user comfort.

In conclusion, the WPI design performed well at 8 psid. Some minor problems such as spherical grip, comfort, and limited thumb motion, could be improved through further design work.

DISCUSSION

Numerous to keys functional glove design were identified. It was determined, perhaps not originally, that radial pressure loads must be carefully controlled and that axial loads must act through the joint centers to retain maximum flexibility. For example, a circular cylindrical section such as a finger supports the radial pressure via the hoop stress on the fabric. The current shuttle glove fingers provide a good example. They are basically circular cylinder sections traced with restraint lines which cause the axial loads to pass through the knuckle joint axes. Application of these fingers, which were developed for 4.3 psi, to the 8 psi design was very successful. Although the loads are greater, use of stronger material provides a flexible, tactile finger.

A non-circular section, such as the metacarpal region which may be considered a cylinder of oval section requires a rigid hoop restraint to control radial pressure loads, as the natural tendency under pressure would be to become circular. The WPI design team's approach uses the MRB which also permits flexibility in the metacarpal region by providing coincident virtual centers which are accessable Other linkages could have been used, but would not serve to contain the radial pressure loads as well.

The thumb root is a two degree of freedom joint, thus a universal joint exoskelton would be required similar to that used in the wrist of the present shuttle glove. The WPI prototype permits rotation about a single axis using a rocker assembly. The full cylindrical grip is retained at the expense of the spherical grip. Further design work is needed in this area.

The palm, being concave, can be restrained by observing that some regions of the palm have no relative motion during grip. Use of a rigid structure such as the Type II clip, which fits these regions, controls palm bulge.

Rolling convolutes and tucks provide for extension of the restraint garment where required. Restraint lines can easily be incorporated where required. Materials are, of course, important for durability and safety, and should be carefully selected.

The key to mobility in glove design is to provide anatomical kinematics while controlling shape changes induced by pressure loads. Non-extension lines, areas of limited or zero deformation, and virtual centers of rotation must be identified and rigidly or semi-rigidly supported. Flexible materials or pleats and convolutes must be used in areas of extension, but must be carefully controlled to minimize volume changes. The WPI prototype glove incorporates these concepts in its design.

The space glove design project was a good example of the type of activity well suited to the WPI Major Qualifying Project degree requirement. First, it dealt with a real problem with elements of conceptualization, analysis, design, fabrication, and testing. In addition, a strict timeline had to be maintained both to meet graduation deadlines and contest entry requirements. One difficulty experienced was that no individual emerged clearly as a student leader which caused some tendency towards group fractionalization and increased the advising burden. This could have been the result, by chance, of the group formation or of the students' inexperience in working in groups of this size.

Independent of whether elements of the WPI prototype are eventually incorporated into the space glove, a significant number of concepts were generated and several were tested. In conjunction with concepts from the other 3 colleges these should provide NASA with many fresh approaches to glove design which can be pursued on a research or contract basis as appropriate.

Finally, this project has broadened the horizons of the faculty involved as advisors. Several faculty from mathematics, materials, biomedical, mechanics, and design diciplines have been exposed to NASA engineers, current technology, and have become knowledgeable in the problems associated with space technology.

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4. "Engineering Design; A Materials Processing Approach", G. E. Dieter, McGraw-Hill, 1983.

Table I

Decision Matrix Criteria

#	Weight	Description
1	.0415	Manufacturability
2	.0393	Heat Transfer
3	.0237	Abrasion/Wear
4	.0698	Palm Bulge
5	.0764	Finger Mobility
6	.0611	Thumb Mobility
7	.0960	Metacarpal Mobility
8	.0679	Protection
9	.0087	Ease of Donning and Doffing
10	.1047	Catastrophic Failure Modes
11	.0022	Weight Limit
12	.0178	Tactility
13	.0468	Degrees of Freedom
14	.0114	Predicted Lifetime
15	.0259	Comfort
16	.0405	User Fatigue
17	.0454	Flexibility
18	.0470	Noncatastrophic Failure Modes
19	.0584	Decompression/Edema Considerations
20	.0149	Inspectional Properties
21	.0178	Ease of Motion
22	.0104	Sizability
23	.0092	Complexity of the Concept
24	.0092	Standardization
25	.0082	Creativity/Novelty of the Concept
26	.0082	Aesthetics
27	.0083	Cost
28	.0164	Clearness of the Concept
29	.0123	Amount of Testing Required
	1.0000	Total

This table was developed using the methods suggested by DIETER (4)

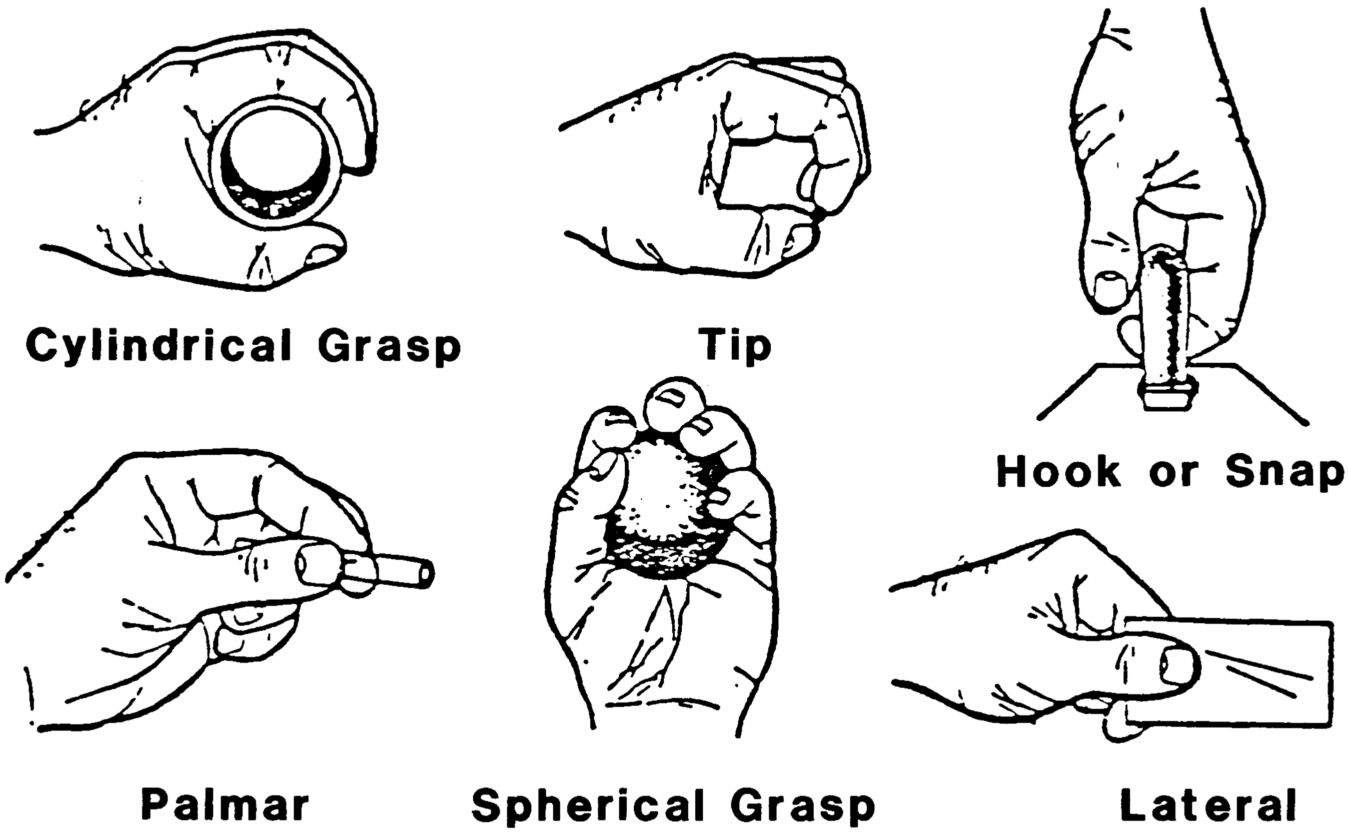


Figure 1 Hand Grip Modes (3)

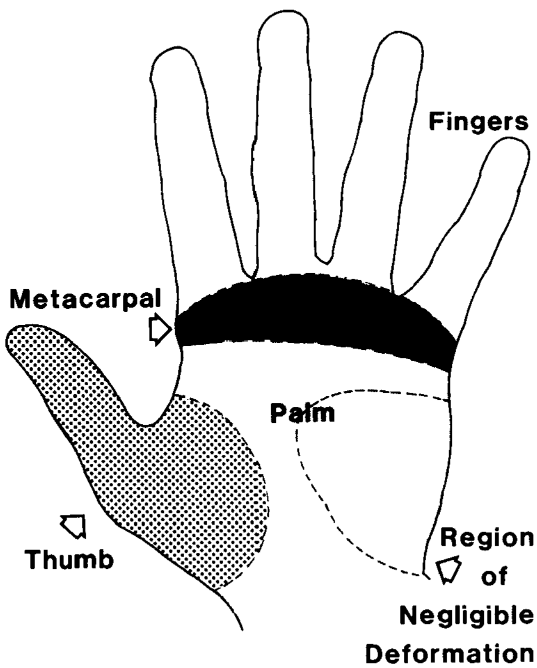


Figure 2 Regions of the Hand

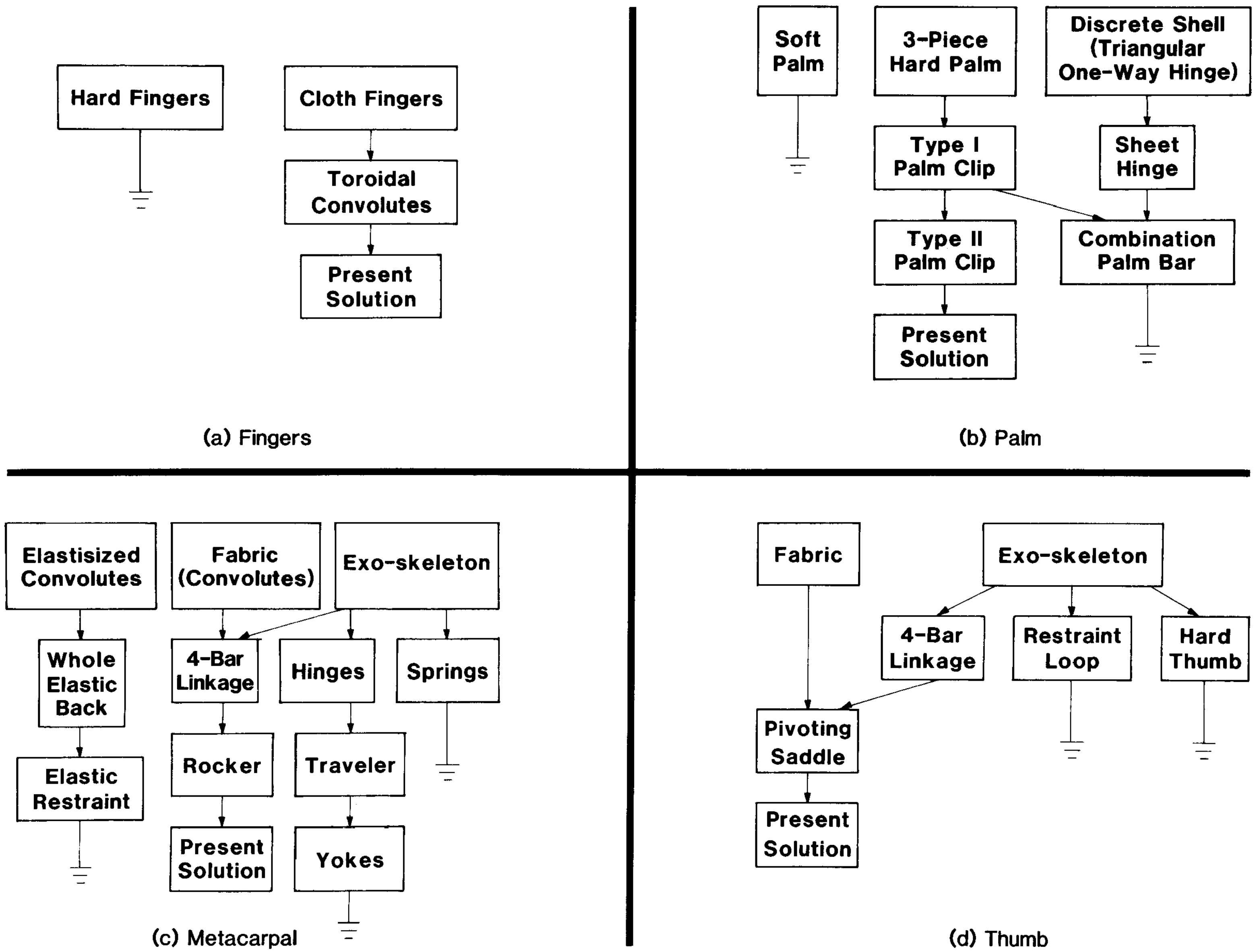
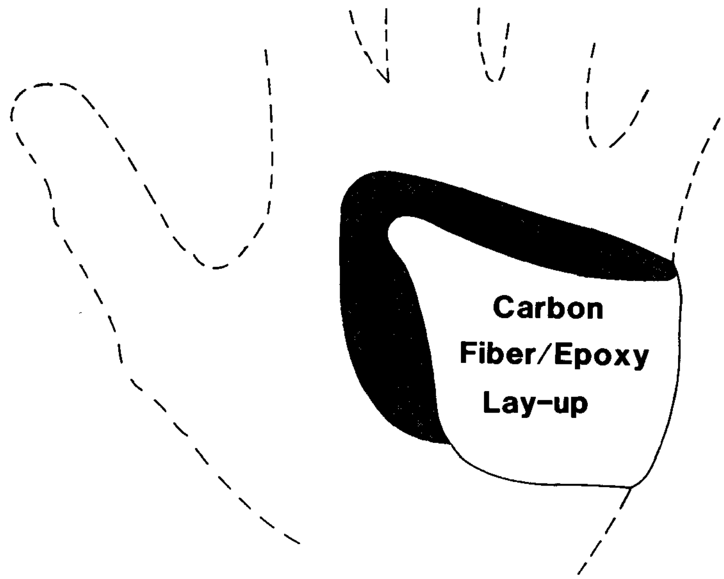
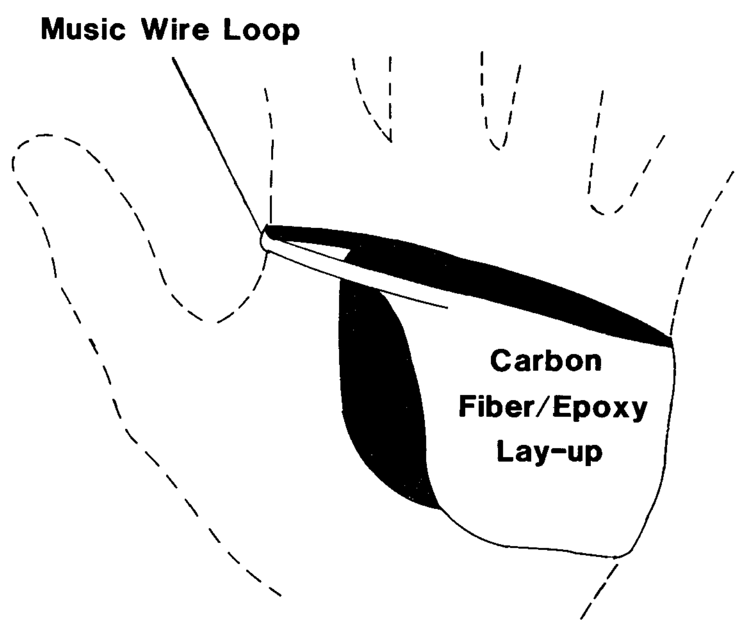


Figure 3 Design Evolutionary Trees



(a) Type I



(b) Type II

Figure 4 Palm Clip Designs

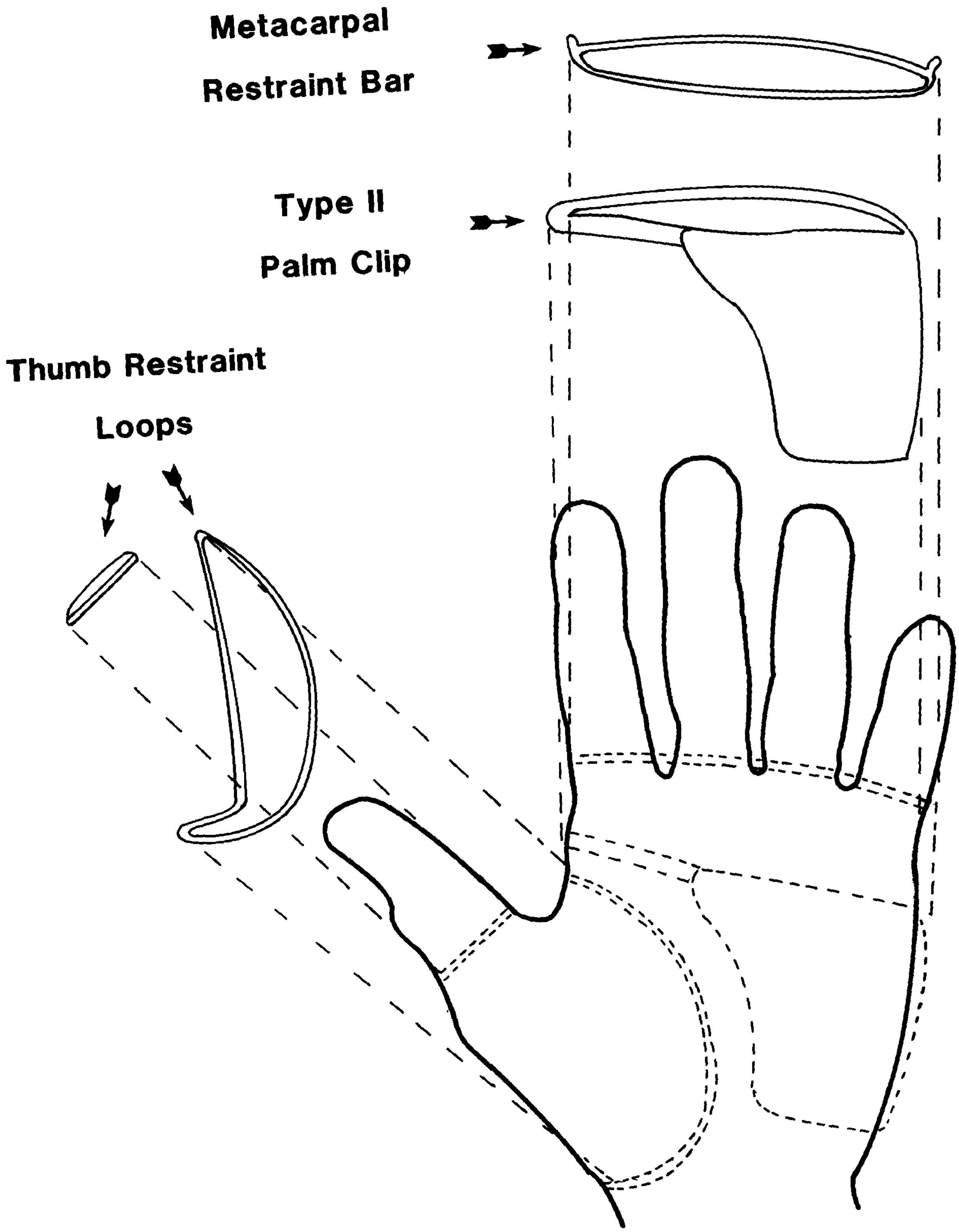


Figure 5 Components of WPI Prototype Glove

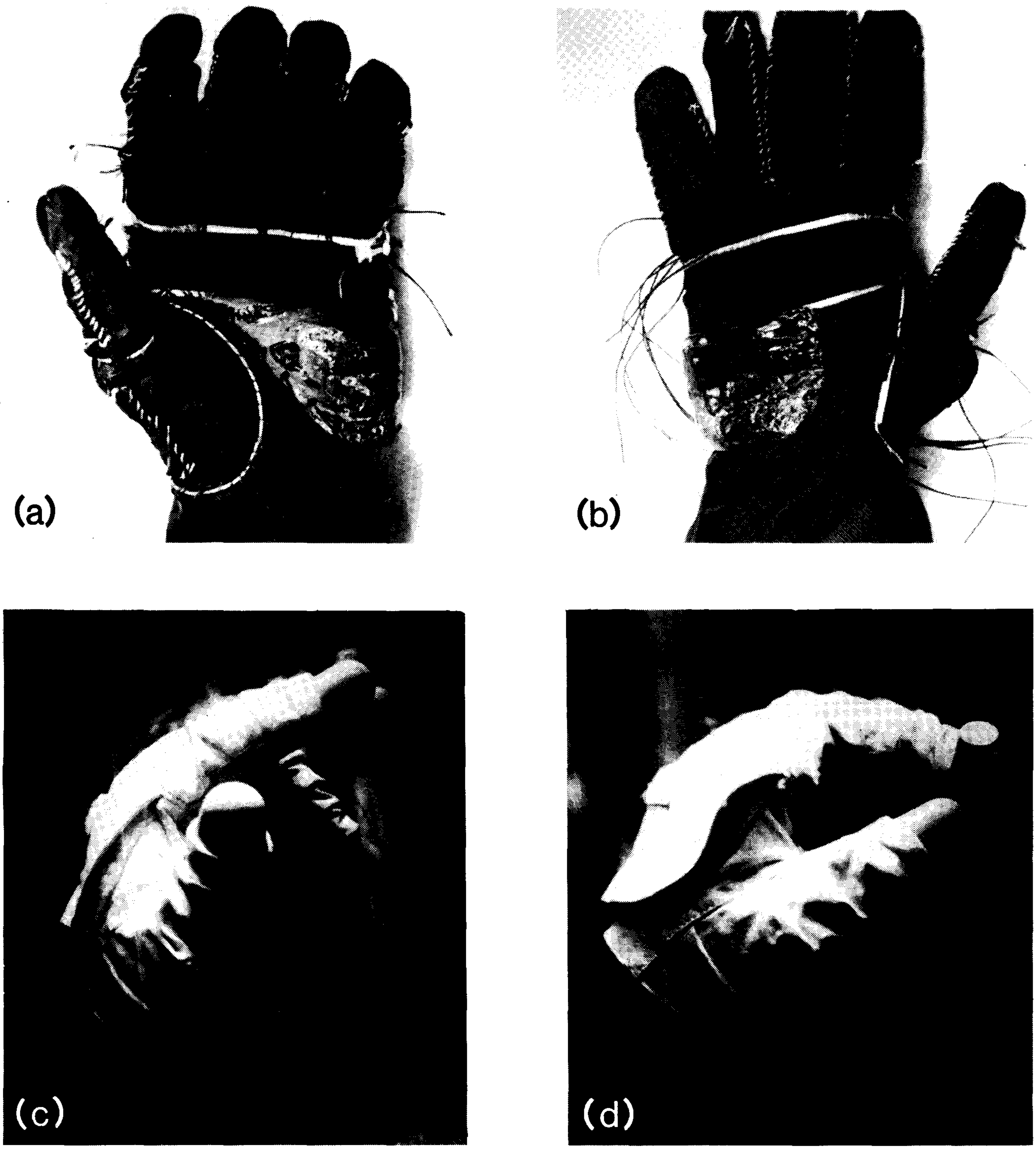


Figure 6 WPI Prototype Glove

(a&b) Restraint Layer, (c&d) With TMG under 8 psid