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The design of a compliant composite crutch

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Abstract—Ambulation by crutches takes up to twice the energy of normal gait and can lead to injuries of the hands and arms. The compliant composite forearm crutch described in this article seeks to address these problems. The new crutch is made of a single composite piece and has an S-curve in the main body to provide shock absorption and return of energy with the goal of reducing impact and repetitive injuries. It is lighter and, we expect, more durable than current crutches due to the lack of interfacing parts. The new forearm cuff design provides retention of the crutch on the arm without a pivot. The contoured forearm cuff with wrist supports and padding is intended to provide added comfort and support. These features are integrated into an aesthetic, high-tech-looking design in charcoal/black color. (See **Figure 1**) Initial testing with seven users yielded favorable response to function and appearance. Quantitative analysis has identified improvements needed for future iteration in design. These include 1) making the wrist supports more narrow and placed down one inch, 2) optimizing the stiffness of the top curve of the S-shape, and 3) testing the crutch for motion and energy requirements in use.

Key words: *compliance, composite material, crutch, cuff, forearm, S-curve, shock absorption, spring return.*

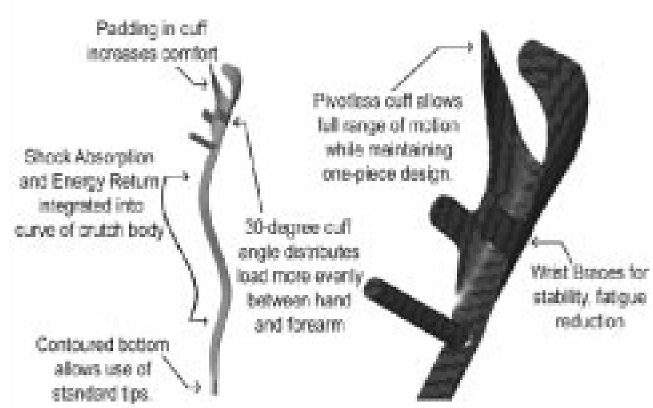

Figure 1.
CAD model of the final crutch geometry.

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INTRODUCTION

Background

Crutches, in one form or another, have been used for 5,000 years (1). From fallen tree branches used to assist balance and ambulation, they have evolved into their present configurations of underarm and forearm crutches. The materials have changed, but the overall design of the crutch is largely the same. They are basically sticks with hand and underarm or forearm supports.

Current crutch designs present some problems for users:

- High-energy expenditure (2): It takes about twice as much energy to ambulate with swing-through crutch gait as it does for normal ambulation. This is due both to the upper body's reaction to the shock of impact and to the vertical movement needed to clear the feet in swing phase by users wearing knee-ankle-foot orthoses with locked knees. The user essentially is doing a body push-up with every step.
- Injuries caused by repetitive loads on the hands, wrists, and arms during ambulation (3–7): These injuries affect many users and are simply stress injuries to the upper limb caused by constant use of crutches. If users have arthritis or other conditions affecting the upper limb, then the effect is compounded.
- Problems created by not standing and walking (8–10): If people do not use crutches because they tire easily or acquire hand/arm problems, there are possible consequences. There are many reasons—physiological and psychological—why it is good to stand and walk rather than sit and use wheeled mobility. These reasons include improved bone growth, improved blood circulation, reduced bladder infections, reduced pressure sores, and prevention of contractures.

Objective

The goal of this project was to ameliorate the problems, as described above, faced by users of crutches. The target user group chosen consisted of permanent users because they have long term and constant need for improvements in crutch design. (Most permanent users utilize forearm crutches, whereas most temporary users utilize underarm crutches.)

Summary of Previous Investigations

This project was preceded by one that compared different kinds of underarm or axillary crutches (11). Four experimental designs of axillary crutches were tested by users and compared to standard underarm and forearm crutches. The four experimental designs were:

- The spring or "pogo" crutch (12–15) with a spring or air cylinder in the upright to dampen the shock of impact.
- The roller or rocker crutch (16–21) with an arc at the tip so that the crutch rolls rather than pivots.
- The suspension crutch (22–23) with a mountain climbing harness attached to the top so that weight is borne partially by the harness and not entirely by the hands.
- The prosthetic foot crutch (24) with an energy-storing prosthetic foot at the tip to absorb shock and provide spring action.

These four designs were tested with users and compared with standard underarm and forearm crutches. Results showed no significant improvement in energy consumption, and therefore none of the designs were selected for further development.

METHODS

The project described in this article was conducted largely by Stanford graduate students as part of a three-quarter design class (25).

Needs Assessment: The first step was to conduct interviews to evaluate current crutch shortcomings. The interviews with crutch users helped to generate a list of design requirements as follows:

1. *Support the weight of the user:* This is of utmost importance for maintaining safety, whether the user is standing, walking, running or climbing stairs.
2. *Employ both shock absorption and energy return:* The crutches should have a means of absorbing shock and also have a way to return energy to the user.
3. *Durable:* This correlates strongly with the weight-bearing capability of the crutch and also the robustness of the interfaces between parts.
4. *Lightweight:* The crutch must be as lightweight as possible to allow ease of maneuverability and low energy consumption.
5. *Maximum mobility:* The crutch cannot be bulky, must allow the user to easily move the crutch tip in any direction, and must easily detach from the user in case of a fall.
6. *Ease of object reach:* The crutch must remain attached to the user while he or she is reaching for an object, opening a door, or shaking hands. (This function is performed in the present forearm crutch by a pivoting cuff.)
7. *Comfort:* Comfort between the arm and the cuff, and the hand and the grip is important.

8. *Silent operation:* One of users' biggest concerns with present crutches is that the pivoting elbow cuff and adjustment holes become loose and produce loud noises.
9. *Support user self-esteem:* The crutch should be attractive and stylish so that it is a personal accessory the user is proud of. [Some crutches are now being made of rosewood and other special materials. See Thomas Fetterman, Inc. (26).]

Testing of Design Ideas

Several quick prototypes were built to test ideas. The first of these was an *angled-cuff prototype*. Angling of forearm support should serve to decrease the load placed upon the hands and wrists. Essentially, the amount of load shifted from the hand and wrist to the forearm is a direct function of the angle at which the forearm is placed relative to the vertical. The angled cuff prototype (see **Figure 2**) allowed exploration of the effect of various placement angles upon the function of a single crutch. The prototype allowed adjustment between 20 and 90 degrees in 5-degree increments. This concept also has been explored by Nils Hagberg (27).

A *wrist support prototype* was produced in response to the pain felt in the hands and wrists of crutch users, caused by the force used to grasp the crutch. As observed in user testing, high grip force is used to maintain stability when the maximum load is applied. To compensate, bracing elements (see **Figure 3**) were positioned on either side of the wrist to stabilize it and allow a more relaxed grip on the handle. Though the design goal was achieved with this prototype, user testing revealed concerns of possible injury resulting from the inability of a user to disengage from the crutch during a fall. (Future iterations of the prototype did not curve around the wrist, but rather were left open for easy arm disengagement.)

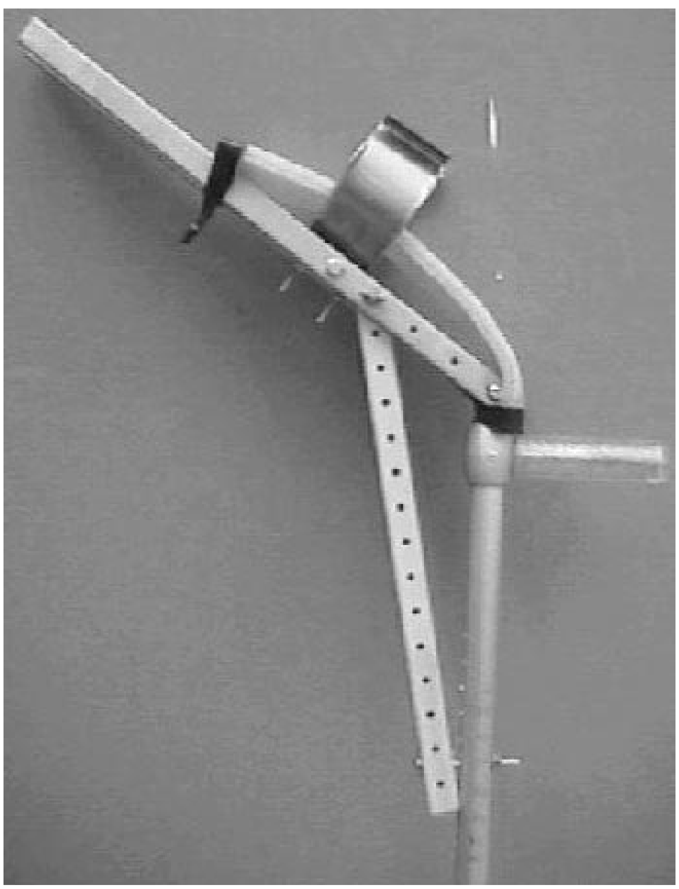

Figure 2.
Angled cuff prototype.

Figure 3.
Wrist support prototype.

A study was conducted to assess the geometry of the *forearm support* to offer the user increased comfort and support. Working under the assumption that the cuff would take the general form of a sleeve or trough that cradled the arm, plaster casts were created of forearms and used as molds to create positive right and left models that were the size and shape of the forearms. Forearm supports were created by heating 0.2-inch thick rectangular sheets of ABS plastic and forming them over the models. The wrist supports eventually were integrated into the cuff. (See **Figure 4**.)

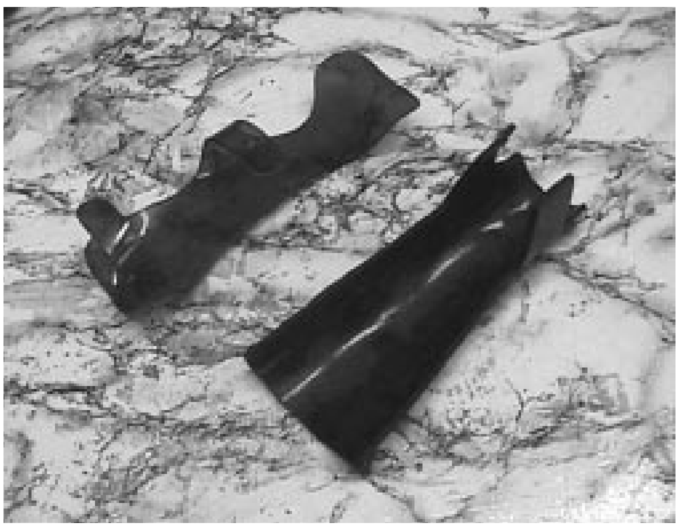

Figure 4.
Forearm support prototypes.

An extensive *spring study* was conducted to determine the spring rate and travel that are optimal for a crutch. The users who were interviewed expressed the need for shock absorption in their crutches. Thirty linear compression springs, with constants ranging from 55 to 409 lb/in, were evaluated by putting them into crutches and testing them with users. The following results were obtained:

1. Any spring that "bottoms out," or reaches the end of its travel so that the user feels an abrupt end to the compliance, is unacceptable.
2. Springs with spring constants greater than 170 lb/in are too stiff and do not feel different than a standard crutch.
3. Springs with spring constants less than 90 lb/in are too compliant for adults.

A graph with suggested spring constants for body weight is shown in **Figure 5**. This graph was developed by taking the qualitative results of user testing and fitting a trendline, called the target value. There is an upper bound and a lower bound to reflect different user preferences determined by maximums and minimums. A spring constant that addresses the needs of the majority of users is 125 lb/in. Referring to the graph, this spring constant, while ideal for a 157-lb person, is also suitable for people weighing 117 to 198 lbs. This range covers 83 percent of the female population and 79 percent of the male population (28). The 125-lb/in spring will travel 0.628 inch for a 157-lb person; 125 lb/in and 0.6-in travel were selected as the design target. The final crutch design assumes customized compliance for different weight classes.

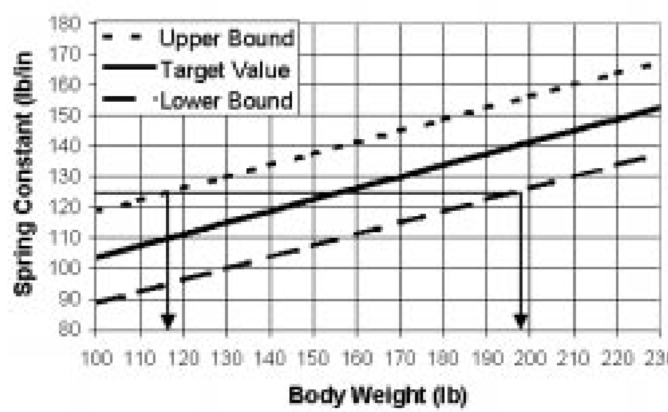

Figure 5.
Suggested spring constant for adults.

Integrating the Design Ideas into a First Prototype Crutch

The goal of the integrated prototype was to incorporate the desired design features into a pair of functional, testable, prototype crutches. A pair of fiberglass crutches that contained helical compression springs and a 45-degree angle cuff was constructed (see **Figure 6**).

The inner core of the prototype was made with a 125-lb/in metal spring press fitted between two wooden rods and secured with epoxy. A block of foam was shaped to create the forearm cuff. The entire crutch core, except for the spring, was laminated with strips of fiberglass cloth dipped in epoxy resin. Concentric carbon fiber tubes shielded the spring. The rough surfaces and exposed fiberglass fibers were sanded, and a final coat of resin was applied for a smooth surface finish.

Figure 6.
Integrated prototype crutch.

A 45-degree forearm angle was chosen for this prototype in an effort to examine the effects of a forearm cuff angle that was furthest from conventional crutches. The following conclusions were made from testing this first prototype.

1. The spring constant of 125 lb/in should be used for future iterations.
2. A simpler way of incorporating shock absorption into the body must be found.
3. The forearm cuff angle should be decreased from 45 degrees to 30 degrees to increase stability.
4. Support for bracing the wrist should be used on either side of the wrist joint.
5. Cuffs should be padded with a soft material to prevent direct skin contact with composite material and to increase comfort.

Final Prototype

The final design was created in three-dimensional CAD. Features identified in the first prototype were incorporated into the final design. Additional design requirements addressed were durability, light weight, ease of object reach, comfort, quiet use, and aesthetics. Carbon fiber composite material was used to fabricate the final design. This approach allowed the spring mechanism to be integrated into the body of the crutch itself, and the entire crutch could be made from one part. We learned that Ergonomics, Inc. also has made forearm crutches of composite material, but used standard round tubes (29).

For incorporating shock absorption directly into the body of the crutch while maintaining a single-piece design, inspiration was taken from prosthetic feet that use combinations of composite material leaf springs to achieve compliance (30). After trials with different geometry configurations, the design team decided on an S-curve design. Compliance was achieved by the two arcs of the S-curve deflecting and acting as a spring. As force is applied, each curve compresses to absorb shock. As force is unloaded, the crutch returns to its original position and returns kinetic energy.

Finite element modeling was used to determine the thickness of the composite cross-section and the amount of curvature that would give the desired compliance (31). Since the S-curved body has a rectangular cross-section, the problem of attaching a conventional crutch tip was addressed by tapering the end of the crutch so that it transformed to a circular cross-section. The handle was incorporated as a simple rod, allowing handgrips of any style to be slipped over it.

The last step in the design was figuring out the geometry for the elbow cuff. The final solution has the two sides of the cuff extending up and around the top of the forearm until the ends are about 2 inches apart. The sides are flexible in order to act as a quick-release mechanism. The posterior underside of the cuff is cut out, thus allowing the crutch to hang vertically as a user flexes his/her elbow. The cuff is curved around the arm and padded to provide support and comfort. The forearm support is at a 30-degree angle and has supports positioned on either side of the wrist joint. The final CAD geometry of the crutch and a close-up of the cuff area are shown in **Figure 1**.

RESULTS

Manufacturing

Sparta Inc. (32), an R&D company with offices in San Diego, CA, designs and develops composite material products, and made the Stanford student-designed crutches using a wet layup method with three different graphite material weaves:

- Hexcel 282 cloth: a balanced 0/90 plain weave,
- XC1131: 90 percent of graphite in vertical direction, for primary bending stiffness,
- CBX 1200: ±45-degree stitched fabric, for torsional stiffness

A mold was constructed by precision cutting a piece of wood using a CNC milling machine to the geometry given in the CAD model of the crutch . The fibers were placed on the mold and coated with resin (see **Figure 7**).

Figure 7.
Fully layed-up crutch on the model.

The final crutches are 0.32 inch thick in the curved section and weigh 20 oz each without tips or padding. Since the layup was not pressurized in the curing, approximately 33 percent less fiber volume and weaker material properties were achieved than if production methods had been used. Production methods would yield a higher fiber volume, meaning that the same performance could be achieved with a thinner crutch. It is estimated that a final production crutch would weigh only 16 oz.

Once the main body was finished, tips, handgrips, and padding for the cuff were attached. Conventional rubber tips and handgrips were used. Custom-made padding was attached to the forearm support using spray adhesive. The final crutches are shown in **Figure 8**.

User Testing

Quantitative testing: Weight, thickness, spring constant, center of weight, bending profile, *et cetera* were measured in the laboratory before user testing. Both static and dynamic loads of up to 250 lb were successfully applied to the crutches prior to user testing.

User profiles: Age, disability, type of crutches, problems in use, *et cetera* were acquired from the subjects before they tested the crutches in use. All users were aged 41–55 years with an average age of 46.5 years. Five of the six users had post polio, and one user had cerebral palsy. All were users of forearm crutches.

User testing: The six subjects were given time to get acquainted with the new crutches and test them in use. Then a questionnaire was administered with 15 topics using a Likert Scale of 1 to 7, with 7 being the best. Highlights of their feedback are as follows:

- How do you like the shock absorption? Most liked that the crutch has shock absorption (5.5 average score) but felt somewhat uncomfortable with the amount of movement (3.4 average score), since they were used to rigid crutches.
- How do you like the one-piece design? Most of the subjects very much like the one-piece design (6.2 average score).
- How do you like the appearance of the crutch? Five were keen on the appearance, and two did not like it being so different (5.1 average score).
- How does the weight and weight distribution feel to you? Most were very pleased with the light weight (6.1 average score).
- How do you like the amount of padding in the cuff area? All were appreciative of having padding to increase the comfort (6.3 average score).
- How do you feel about how quiet the crutches are? All very much liked that they are not noisy like their present crutches (6.8 average score).
- How do you feel about the stability of the crutches? Most felt somewhat apprehensive about the movement and stability of the crutches (3.2 average score) because they are so much different than their present crutches that have no flexibility. Dimensions of the fabricated crutch were best suited for a 100- to 130-lb person. Heavier users said that the crutches were too compliant.

Overall, user feedback indicated that the general design appears to be an improvement over current fore-

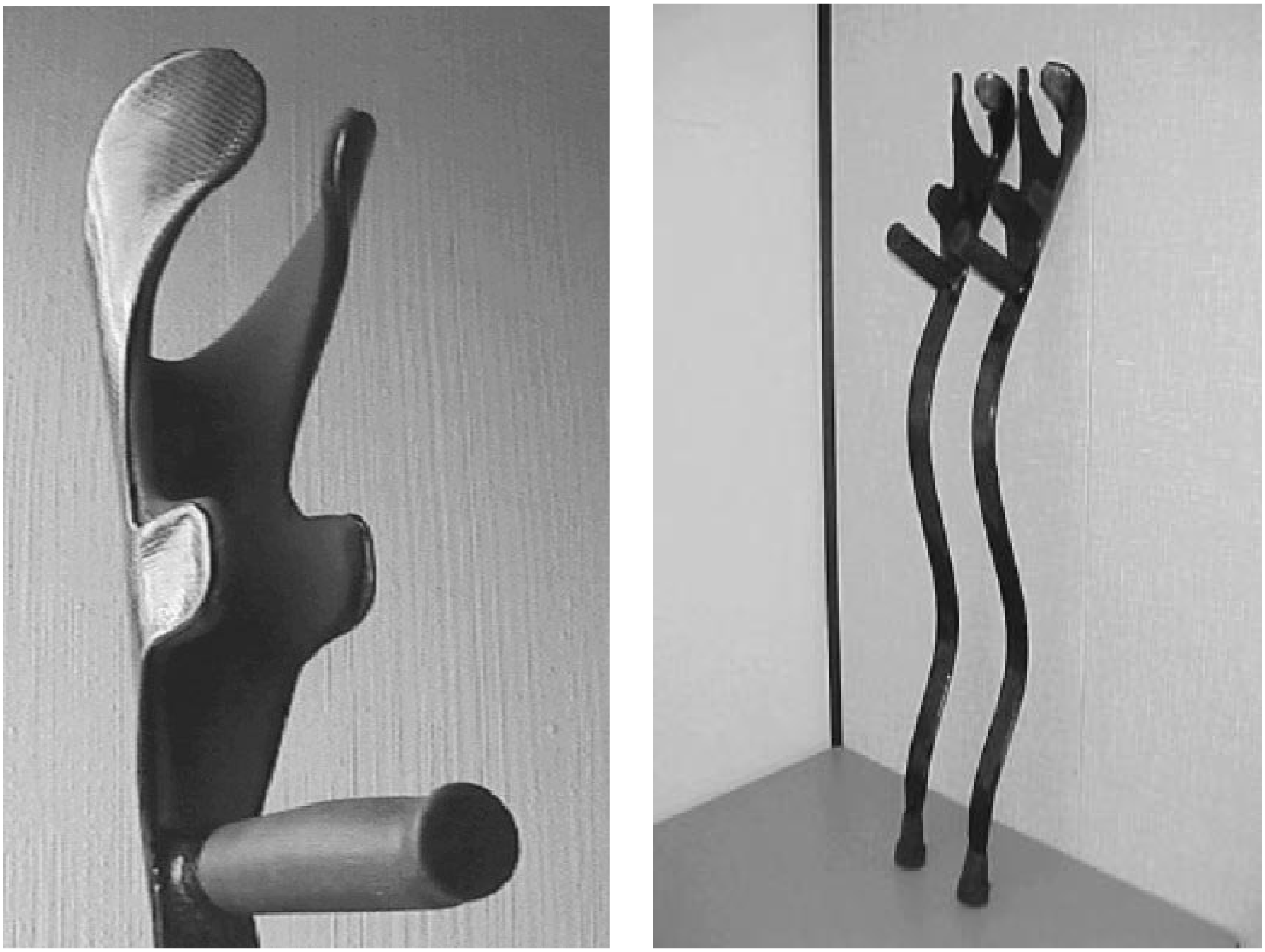

Figure 8.
Final crutches.

arm crutches, but improvements are necessary to meet all their needs.

Biomotion Laboratory Testing

Experimental testing was done in the Stanford University Biomotion Laboratory (33). The crutch was loaded from 0 to 100 pounds over a period of 2 seconds. The force applied to the ground and the three-dimensional position of the photo-reflectors attached to the crutch were measured. From this data, it was possible to calculate the stiffness of the entire crutch and the S-curved portion as 43 lb/in and 211 lb/in, respectively.

The resulting stiffness values showed that the crutch is deflecting in two different manners. The first deflection is in the S-curve and is what was originally planned for. The second deflection is due to the bending of the cuff posteriorly. This latter deflection causes the crutch to be more compliant and creates a feeling of instability in heavier users.

Finite Element Model

The goal of the finite element analysis after user testing was to optimize the bending behavior for the crutches. It was found that the level of deflection in the S-curve was dwarfed by the bending moment created by the cuff at the top of the crutch. The finite element software ANSYS was used to run the analysis (31).

There were four possible parameters that could reduce cuff bending: increasing the thickness of the upper curve, decreasing the cuff angle, reducing the amount of

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curvature of the top curve, and changing the apex of the top curve. Changing the thickness of the upper curve was undesirable, since it would complicate the manufacturing process. Decreasing the cuff angle was unfavorable because the hands would have to carry more load. Therefore, the solution was chosen to change the curvature and apex of the top curve. The final optimization moved the top curve up 1.0 inch and inward 0.5 inch (**Figure 9**).

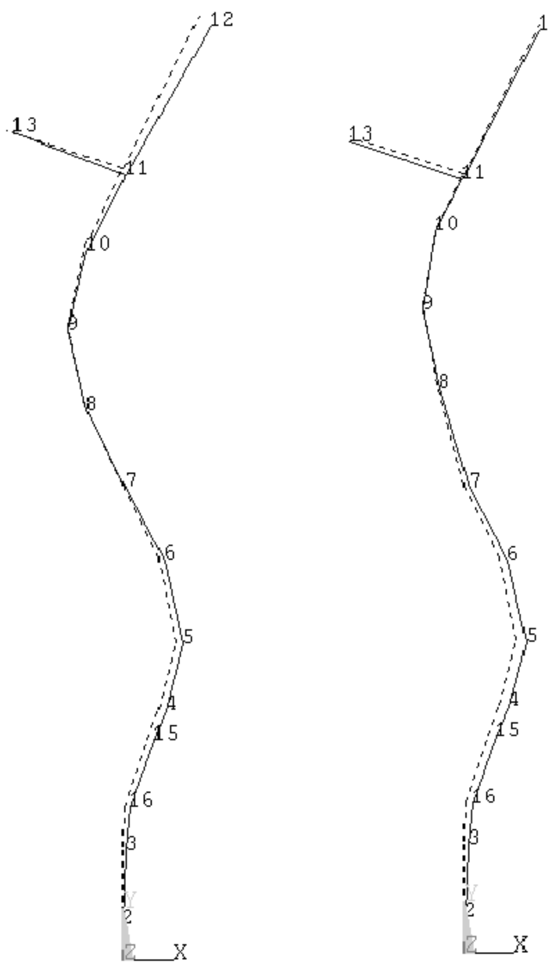

Figure 9.
Two-dimensional finite element representation of original curve of crutch (left) and optimized curve (right).

DISCUSSION

The final design of the compliant composite crutch addresses some of the needs expressed by permanent crutch users. Its single-piece composite design reduces noise. Shock absorption and energy return are addressed with the S-shaped body that acts like a spring. The energy that is stored in the beginning of the gait cycle theoretically is returned to the user at the end of the gait cycle. Energy testing is needed to confirm that assumption. The forearm cuff design gives added support and comfort, while allowing users to maneuver and reach for objects. Users liked the charcoal/black, high-tech appearance of the crutches.

Future Improvements

The positive responses from testing by crutch users of the compliant composite crutch are encouraging. However, this design must go through additional design iteration before it is ready as a product. Needed improvements include:

- Refinement of the direction of shock absorption in the top curve using the optimized geometry developed in the finite element model.
- Modified geometry for the wrist supports so that they do not interfere with wrist watches. We recommend moving them down by one inch and reducing them to two-thirds their original width.
- Testing of energy consumption in ambulation by crutch users.

Vision of Final Product

Ultimately, the crutch may be a semi-custom product that is selected for each individual, much like the FlexFoot in lower limb prosthetics (30). The S-curve of the crutches can be made in different thicknesses to achieve desired compliance for users of different weights, such as light, medium, and heavy. The crutches would be cut to length on the height of the crutch from floor to handgrip. All crutches could be manufactured at the longest possible length and then cut to the size for each user. The fitting of the cuff could be addressed by making a large cuff with accommodation for smaller forearms by using extra padding. Users could specify handgrips and tips of choice.

The relatively high cost of manufacturing the crutches is a potential problem. Composite materials are typically high in cost. To keep the crutches reasonably priced, manufacturing processes would have to be explored further. Possibilities include using fiberglass instead of carbon fiber and making the S-curve of composite material with the forearm cuff made separately by a one-piece injection-molded part.

An idea for improving the design of the crutch is to make it foldable. Many crutch users want their crutches to be compact for travel or storage. This design could be adapted to fold in half by adding a hinge between the two curves, at the point of lowest stress, so that one curve nests in the other curve. Another suggestion by one of the crutch testers is to place a small reflector on the end of the handgrip and on the back of the forearm cuff for visibility at night.

CONCLUSIONS

The compliant composite crutch prototype addresses many of the concerns of crutch users. Their positive feedback is encouraging. However, the potential benefits must be proved and documented with further study. Design improvements, as discussed above, need to be implemented. The goal is that through further redesign, analysis, and testing, the compliant composite forearm crutch will offer improvement to permanent crutch users.

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REFERENCES

1. Epstein S. Art, history, and the crutch. Ann Med Hist 1937;9:304–13.
2. Fisher S, Patterson R. Energy cost of ambulation with crutches. Arch of Phys Med Rehabil 1981;62(6):250–6.
3. Waring W, Werner R. Clinical management of carpal tunnel syndrome in patients with long-term sequelae of poliomyelitis. J Hand Surg 1989;14A:865–9.
4. Puttenshaw P. Joint problems in amputees. Step Forward 1995;39:1–2.
5. Joint problems: a real pain. Paraplegia News. 1995;49(7):37–42.
6. Deathe A, Hayes K, Winter D. The biomechanics of canes, crutches, and walkers. Crit Rev Phys Rehabil Med 1993;5:15–29.
7. Malkan D. Bilateral ulnar neuropraxia: a complication of elbow crutches. Injury 1992;23:426.
8. Bruno J. Energy cost of paraplegic locomotion. Clin Podiatr 1984;1(2):291–4.
9. Axelson P, Gurski D, Lasko-Harvill A. Standing and its importance in spinal cord injury management. Proceedings of 10th Annual RESNA Conference. San Jose, CA, Washington, DC: RESNA Press; 1987. p. 477–9.
10. Rovick J, Childress D. Pendular model of paraplegic swing-through crutch ambulation. J Rehabil Res Dev 1988;25(4):1–16.
11. LeBlanc M, Carlson L, Nauenberg T. A quantitative comparison of four experimental axillary crutches. J Prosthet Orthot 1993;5(1):20–8.
12. Lewin P. An adjustable spring crutch. J Bone Joint Surg 1928;10:819–21.
13. Shoup T. Design and testing of a child's crutch with conservative energy storage. Trans ASME 1980;102:672–6.
14. University of Colorado. A modified crutch design using a gas spring. ME 416 Report. Spring 1982. Lawrence E. Carlson, DEng., Instructor.
15. Parziale J, Daniels J. The mechanical performance of ambulation using spring-loaded axillary crutches. Am J Phys Med Rehabil 1989;68(4):193–5.
16. Joll C. An improved crutch. Lancet 1917;1:538.
17. Hall R. A rolling crutch. JAMA 1918;70:666–8.
18. Nielsen D, Harris JM, Minton YM, et al. Energy cost, exercise intensity, and gait efficiency of standard versus rocker-bottom axillary crutch walking. J Phys Ther 1990;70:487–93.
19. Gillespie F, Fisher J, Williams C, McKay E, Curr M. A physiological assessment of the rolling crutch. Ergonomics 1983;26(4):341–7.
20. Basford J, Rhetta H, Schleusner M. Clinical evaluation of the rocker bottom crutch. Orthopedics 1990;13(4):457–60.
21. Switkes J, Hsieh D. Students at Athenian School, Danville, CA Developed rolling crutch prototype. Teacher: Eugene Mizusawa, PhD. (http://www.athenian.org)
22. Taylor J. A new saddle-crutch. Med Rec 1983;24:136.
23. Kaplan M, Naglreiter B. Comparative energy expenditure of swing-through crutch gait with axillary, suspension, and modified suspension crutches. Draft journal article for J Rehabil Res Dev 1994.
24. Quantum Foot, Hosmer Dorrance Corp., P.O. Box 37, Campbell, CA, 95008, (408) 379-5151.
25. ME210, Team Based Design Development, Mark Cutkosky, PhD, Teacher, Terman 523, Stanford University, Stanford, CA 94305.
26. Thomas Fetterman Inc., P.O Box 174, Dept A, Southampton, PA 18966, (www.fetterman-crutches.com).
27. Hagberg N. US Patent # 5,671,765. (510) 530-6701, 4219 Maple Avenue, Oakland, CA 94602-4046.
28. Dreyfuss, Henry & Associates. The Measure of Man and Woman: Human Factors in Design. New York: Whitney Library of Design, 1993.

29. Ergonomics Inc., 6058 Mad River Road, Dayton, OH 45459, 937-434-2466, ergocrutch@aol.com. Joyce Young, president; Steve Gustafson, Ph.D., vice president of technology.
30. Flex-Foot, Inc., 27412-A Laguna Hills, Aliso Viejo, CA, 92656, 800-233-6263, www.flexfoot.com, contact: Van Phillips.
31. ANSYS finite element software package (www.ansys.com).
32. Sparta Inc. 10540 Heater Court, San Diego, CA 92121, 619-455-1650; contacts: Joel Zuieback, Tom LaCombe, Walt Whatley.
33. Stanford University Human Biomotion Laboratory, Building 530, Stanford, CA 94305; contacts: Dr. Thomas P. Andriacchi, Dr. Gene Alexander, Chris Dyrby.

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