

The Evolution of Upper Limb Prosthetic Socket Design

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ABSTRACT

Well thought out socket designs and careful consideration of residual limb presentation set the stage for patient success—maximizing range of motion, providing stability throughout daily activities, and comfortably distributing the forces exerted on the residual limb during movement and suspension. In contrast, poor socket design will often drive people to abandon the prosthesis because many patients have an intact arm or hand. The foundation for all prosthetic procedures is a well designed and considerate prosthetic socket. The purpose of this article is to shed light on the many variables behind the evolution of upper limb socket design. Review of historical literature reveals two distinct and major influences—material science and the emerging upper limb prosthetic specialist. (*J Prosthet Orthot.* 2008;20:85–92.)

KEY INDEXING TERMS: upper limb, prosthesis, prosthetic socket, evolution of socket design, prosthetic material science, upper limb prosthetic specialist

One of the single most determining factors of whether a person will use a prosthesis is prosthetic socket design. In the words of Hepp¹ “the degree to which the prosthesis fits the stump will make all the difference.” Well thought out socket designs and careful consideration of residual limb presentation sets the stage for patient success—maximizing range of motion, providing stability throughout daily activities, and comfortably distributing the forces exerted on the residual limb during movement and suspension. In contrast, poor socket design can drive people to abandon the prosthesis because many patients have an intact arm or hand.² Clinically, this decision becomes detrimental years later when repetitive stress syndrome compromises the remaining natural limb, causing pain and loss of function. Other causes of prosthesis abandonment include functionality of componentry, weight, and time to fitting and follow up.² Irregardless of the cause, prosthesis abandonment is a serious problem that should be avoided whenever possible given the likelihood that repetitive stress syndrome may develop in individuals that rely heavily on one arm for daily tasks.^{3–5}

The foundation for all prosthetic procedures is a well designed and considerate prosthetic socket. The purpose of this article is to shed light on the many variables behind the evolution of upper limb socket design. Review of historical literature reveals two distinct and major influences—material science and the emerging upper limb prosthetic specialist.

A HISTORICAL PERSPECTIVE

Ironically, as this article was being researched and written, the author was reminded of a grade school oral report he had presented 25 years earlier on Ambrose Pare. Pare’s discover-

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Disclosure: The author declare no conflicts of interest.

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ies, which revolutionized amputee care, remain relevant for both school children and medical professionals. During Pare’s time, doctors cauterized gunshot wounds with boiling oil. It was not until Pare ran out of oil in a battle that he began to use simple dressings and soothing ointments that resulted in a marked improvement in his patients. Pare’s advances in wound care helped more amputees survive. He also discovered that ligation of blood vessels controlled bleeding during amputation.⁶ Pare went on to conceptualize many different orthotic and prosthetic designs for both upper and lower limbs.

Up until 1900, most references to upper limb prosthetics is found in literature relating to warfare and similar conflict. Then in 1905, Marks made an important observation. He observed that the demand for upper limb prosthesis had grown with the emergence of early 20th century industry. He noted the increases in limb loss with the transition from black powder to dynamite, from horse-cars to electric trolley, and from the scythe or cradle to the mowing machine.⁷

Not until the mid 20th century does discussion of socket design crop up in upper limb prosthetic literature. Hepp seems to be the first to state the importance of a correctly fit socket and how this issue had been ignored for upper limb patients despite the fact that clinicians had long focused on socket design for lower limb amputees. This concurs with this author’s review of pre-1900 prosthetic literature.^{7–12} Hepp’s comments were likely the starting bell that began the push toward better fitting upper limb sockets. Hepp states that:

“if the socket fits firmly and well on the stump, there is little or no strain on the harness when the prosthesis is used to carry or hold various articles. If the socket fits well and is pressed firmly to the stump, it will effectively withstand any pressure and transmit force against any object and at the same time transmit force from parts of the harness to the mobile parts of the prosthesis. Should the socket be without any rotary motion or fitted so well that the possibility of ridges developing in the stump be eliminated, then the danger of pseudoarthrosis between the socket and stump is reduced to a minimum and every movement of the artificial

arm in the region of the stump can be purposefully made when performing rough or exacting work. An anatomically correct fitting gives the amputee a feeling that his artificial arm is really a part of his body.”¹

TRANSRADIAL

The developments of Hepp and Kuhn in the mid 20th century, Otto Fruzinsky in the 1960s and later Billock in the early 1970s, provided the foundation for today's transradial socket designs.¹³⁻¹⁸ Each of these designs built upon the last. Where the Muenster type socket of Hepp and Kuhn, specifically designed for short transradial applications, focused on anteroposterior stability at the proximal brim, the Northwestern University Supracondylar Suspension Technique is considered to be more medial-lateral focused and accommodated longer residual limbs. Important to note is that the Northwestern technique takes great care to discuss the biomechanics of the socket design as it relates dynamically to the range of motion of the residual limb. The degree of investigation of the Northwestern design is the initiation of the prosthetist looking beyond the brim of the socket and considering the biomechanics of socket design.¹⁷ Otto Fruzinsky is credited with the progressive designs of the Otto Bock style Muenster introduced with the MyoBock system in 1968 and taught as part of the MyoBock Certificate Courses (J. Uellendahl, personal communication, 2008). Ultimately these design considerations and clinical experience allowed a transition into more anatomical considerate designs in the 1990s.^{19,20}

Transradial socket designs have seen the influence of Sauter with the initial concept of the 3/4 socket design²¹ (Figure 1) and more radical concepts such as the Ergonomic Socket Design from the Netherlands²² (Figure 2). Both designs recognize the socket purpose and the need to provide cooler socket temperatures. For Sauter, the socket's posterior proximal portion served no apparent purpose, so he removed it and provided a window. The Netherlands team focused on creating an economical socket that was easy to don. The resulting frame design considers anatomical structures and



Figure 1. 3/4 transradial socket.

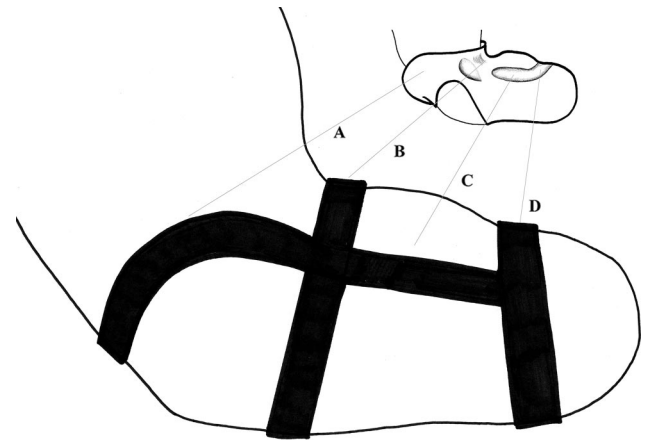


Figure 2. The ergonomic socket design conceptualized in 1985 was constructed of stainless steel tubes that were placed in anatomical regions to maximize the biomechanical efficiency of the design. These structural placements are similar to the region of anatomical consideration in the anatomical considerate transradial designs of today. A. Supra-condylar contour to promote medial-lateral and rotation stability. B. Ante-cubital/Supra-olecranon channel to enhance anterior-posterior stability. C. Wrist flexor/extensor channel to enhance weightbearing. D. Distal radial channel to allow weight-bearing proximal to the cut end of the radius.

biomechanical principals with a unique connection for the structure distal to the socket.

TRANSHUMERAL

The first diversions from traditional transhumeral design were the socket designs by McLaurin et al. and Pentland and Wasilieff in the 1960s and 70s.^{23,24} These socket designs are characterized by a reduction in the socket's lateral trim line and greater stability and mobility provided by the modified trimlines. With the introduction of the Utah Arm, Tom Andrew expanded on the early work of the aforementioned authors an aggressive modification into the deltopectoral groove anteriorly and a flattened region posteriorly just inferior to the spine of scapula.

The concepts discussed by Andrew in the 1992 Edition of the Atlas of Limb Prosthetics. Andrew's socket design, expanded on the early work of his predecessors in the 1960s and 1970s (Figure 3). This residual limb contouring provided greater rotation control, enhanced range of motion, and reduced the harnessing requirements characteristic of more traditional designs.²⁵ Andrew's design has endured over the last 15 years with only suggested modifications to the medial wall and proximal trim line. Alley¹⁹ noted that this wall at times can be excessive and make donning difficult and suggested alternatives. Whether the medial wall is represented by the characteristic lateral directed pressure and concavity that is considerate of the tendons coursing the anterior and posterior aspects or more of a gradual flare, these suggestions are patient specific and knowledge of socket variations certainly enhances prosthetic socket armamentarium.



Figure 3. Transhumeral socket (anterior view) based on Andrew's dynamic socket.

SHOULDER

Prosthetic management of the shoulder level has always been a challenge. Excessive heat buildup is a common complaint.²⁶ At the shoulder or associated level of limb deficiency, a frame shoulder design that considers anatomical contours and uses trim lines that minimize residual limb coverage is preferred. This approach dissipates heat better and dramati-

cally enhances stability in contrast to more encapsulating designs. Well known to the field were the frame designs advanced by Sauter.²⁷ Unique to this time period and not as well known was the introduction of carbon reinforced plastic designs for reinforcement of the frame structure.^{28,29} This is an important note as this represents an early reference to composite technique in the field and importantly a 30% to 40% weight savings as compared with the metal frames of the day. As noted by Miguelez et al.³⁰ these early frames are considered more of a "perimeter frame" as these designs did not use anatomical contouring of today's more progressive socket designs.

In the late 1970s, Eric Baron and Mark Mosely begin to discuss their idea of a more anatomically considerate frame design. (J.T. Andrew, personal communication, 2008) (Figure 4). Like Sauter, Barron and Mosely incorporated metal but in contrast added contoured plastic to better distribute force. In the early 1980s, Andrew conceived and executed the concept of an all thermoplastic frame. Perhaps because of prosthetists' long time aversion to anything resembling orthotic metal bending, the all thermoplastic design of Andrew's Mini-Frame marked an important first. This design allowed for significant force distribution and stability for the shoulder level through appreciation of the weight tolerant anatomical structures (Figure 5).³¹ Later designs including Alley's X-frame^{19,26,32} and Miguelez's Microframe^{33,34} built upon the early work of Barron, Mosely, and Andrew. The frame shoulder design uses anterior to posterior compression principles and muscular considerate trim lines to help maintain suspension and prosthesis stability. These designs result in a stable foundation for advanced systems necessary for this highly compromised patient population.

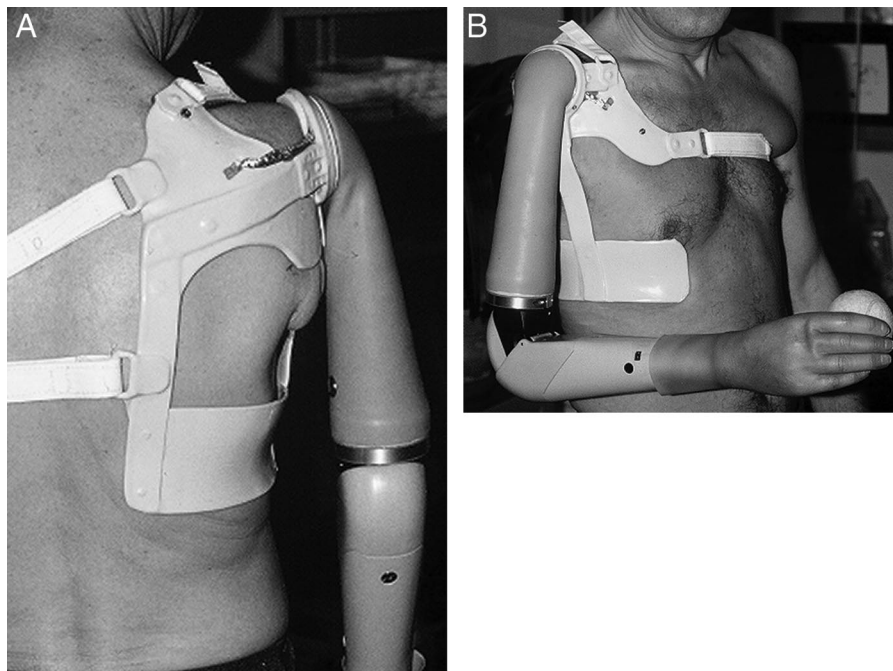


Figure 4. Shoulder frame socket by Baron and Mosely, approximately in 1980 (courtesy of Tom Andrew, CP, FAAOP). A, Posterior view. B, Anterior-lateral view.

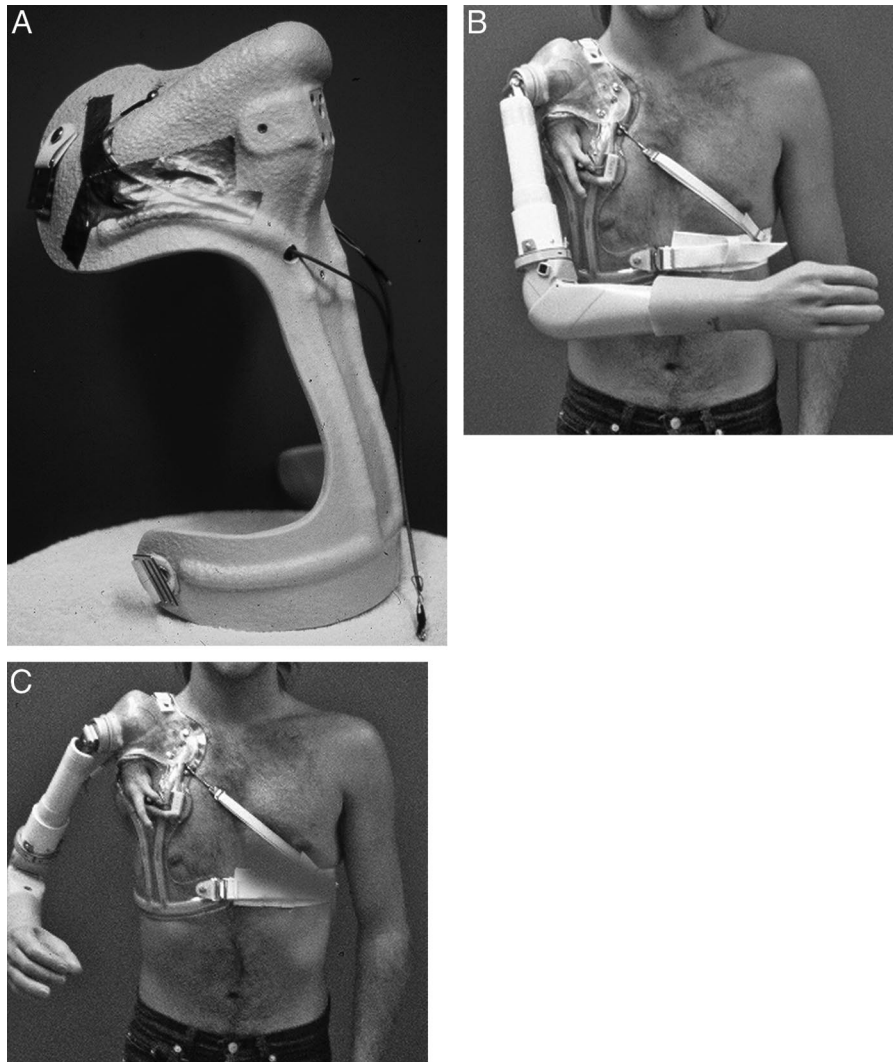


Figure 5. Early shoulder frame designs, approximately in 1980 (courtesy of Tom Andrew, CP, FAAOP). A, Andrew's mini frame made entirely from Kydex. B, Andrew's mini frame illustrating enhanced stability.

Progress Through Synergy

One significant move forward occurred during the 1990s with the conception of the NovaCare Upper Extremity Prosthetic Program led by John Miguelez (J.M. Miguelez, personal communication, 2008). This marked the first formal group of practitioners united for the common purpose of specializing in and advancing upper limb prosthetics. Though most of their developments were proprietary in nature, it was the first time a sizable group of prosthetists looked beyond the brim when designing the socket. The program's synergy helped catalyze upper limb prosthetic development. This program, acquired by the merger with Hanger at the turn of the millennium, still pushes the art of upper limb prosthetics and in a more public way, allowing the field to grow from their collective experience.

As the 20th century came to close, more oral presentations focused on anatomical socket design. Most of these presentations were exclusive to the University of New Brunswick MyoElectric Controls/Powered Prosthetics Symposium (MEC).

In the absence of abundant written information, the MEC Conference, which commenced in 1972, provided the primary global forum for upper limb knowledge exchange and debate. Frame socket concepts for the shoulder levels were discussed formally by Miguelez and were noted or illustrated by many others in the 1999 MEC Conference.³⁵

Alley at the 2002 MEC Conference ushered in a new era with the first comprehensive look at the effects of the anatomically contoured and controlled sockets at the transradial, transhumeral, and shoulder levels.¹⁹ Alley built upon the work of his predecessors and added significant emphasis on the biomechanics of socket design. Since that time, a renewed focus on socket design has resulted in many professional journals and books publishing progressive techniques in upper limb socket design.^{20,26,33,34}

Socket Design as a Result of Material Science

As socket designs have evolved, so have prosthetic materials. Early prosthetists touted how well wood sockets

could be shaped to mirror the residual limb. Discussion of the benefits of specific force distribution of lower limb applications was common in pre-1900 prosthetic text. The widespread use of measurements yielded to the more exacting duplication of residual limb contours through plaster impressions. Wood and leather succumbed to aluminum and laminates.⁷⁻¹² Most important to socket design was the wide acceptance of thermoplastics. Thermoforming yielded more contoured sockets. Transparent materials allowed for critical analysis of socket dynamics beyond the proximal brim and essentially reduced the “bench time” of the prosthetist working wood and leather and increased the clinical time.³⁶⁻³⁹ Sockets became more flexible and comfortable. Additionally, more flexible materials allowed the prosthetist to be more anatomically conscious as the more aggressive contours enhanced stability while at the same time maintaining ease of donning. Plastics flexibility, the differing shore values of silicones and urethanes, and the understanding of composite lamination and construction materials continue to drive upper limb prosthetic socket design today.⁴⁰⁻⁴⁴

Current Perspective—Socket Design as a Result of Thinking and Experience

The field of Orthotics and Prosthetics has enjoyed significant advances in the last 25 years. As our field pushes further into research and development endeavors, we have begun to find ourselves focusing on specified interests of practice. Evidence of this is clearly seen in the formation and promotion of specialty societies within the American Academy of Orthotists and Prosthetists. Our field is entering a time reminiscent to the era that medicine navigated nearly a century ago.

Between 1916 and 1930 most of the current 24 medical specialties were conceived and developed. Whether for reasons of specific focus on systems of the body, particular ways of thinking, or the use of technology, medical specialties have given rise to medical advances that were only possible with such a focused approach. By the mid 20th century, medicine was no longer a profession where being a generalist was an option.⁴⁵

Today subspecialties are readily seen in orthotic practices. Within large practices there are individuals who focus their professional endeavors on trauma and fracture management, pediatric orthotics, spinal deformities and trauma, cervical trauma management, and pediatric cranial deformities. Each of these focused endeavors requires a unique skill set to maximize patient care and outcomes.

The emerging specialty of upper limb prosthetics and focused therapy was highlighted by Atkins and Alley⁴⁶ in 2002. Furthermore the need for synergy, clinical debate and professional relationships in our efforts will assure that upper limb prosthetics is not overshadowed by the increasing numbers of lower limb loss.

DISCUSSION

TODAY'S UNIQUE UPPER LIMB LOSS DEMOGRAPHIC CHALLENGE

Many challenges exist when treating individuals with upper limb loss. Aside from the physiological, sociological, psychological issues, the relatively small size of this patient group has meant that general prosthetists are often unfamiliar and/or inexperienced with the highly complicated fitting needs of this group. There is a 30:1 lower limb to upper limb patient ratio when one averages the adjusted numbers, Dillingham et al.⁴⁷ found in their review of the epidemiology of limb loss in the United States. This ratio is a conservative estimate, based upon the most common levels fit—Symes to hip disarticulation and wrist disarticulation to shoulder disarticulation. This lopsided ratio is the crux of what prosthetists call the “upper limb dilemma,” whereby the most challenging cases are dispersed among practitioners who see such cases rarely and have fewer opportunities to hone their upper limbs skills, much less keep apprised of new devices, fitting techniques or therapy.

The second challenge relates to the expected growth in lower limb loss in this country. A rigorous analysis by Ziegler-Graham et al.⁴⁸ predicts that the prevalence of limb loss in the United States will more than double from the 2005 figure of 1.6 million to 3.6 million in the coming decades. Broken down further—1 out of 190 Americans live with limb loss today. By 2050, that number will approach 1 out of 100. An aging population and increasing rates of obesity and vascular disease are driving this increase. Assuming that the incidence of upper limb loss remains steady, upper limb patients will represent an even smaller proportion of those with limb loss. If US upper limb cases decrease, a trend Heckathorne noted in his 2001 invited talk at the ISPO World Conference in Glasgow Scotland, these patients will have an even tougher time finding a general prosthetist with any experience fitting upper limb cases (C. Heckathorne, personal communication, 2008). Heckathorne used world census data to show generally declining or static populations in most of the more developed countries and significantly increasing populations in the less developed countries. He speculated that the future of upper limb prosthetics was in the less developed countries because of the shift of manufacturing and industrialized farming to those countries, generally less safe industrial environments, greater likelihood of major armed conflicts, and fewer medical resources to save injured limbs.

The third demographic challenge—the number of qualified prosthetists in the coming years, further complicates the upper limb scenario. In 2006, a workforce demand study was performed for the National Commission on Orthotic and Prosthetic Education and the American Orthotic and Prosthetic Association.⁴⁹ A 0.5% net growth in certified orthotists and prosthetists is expected through 2010. After 2010 through 2030, a growth rate between 1.45% and 2.4%, depending on the addition of two new schools, is expected. Unfortunately, this modest influx of new practitioners will be erased by the projected 3.33 attrition rate. Clearly, these

demographic forces are setting the stage for some very busy lower limb practices, in which individuals with upper limb loss could truly be lost in the crowd of lower limb patients and increasing numbers of serious vascular cases.⁴⁸

CONCLUSION

The concept of more anatomically appropriate socket designs took root long ago. Generations of prosthetists have dreamed and experimented, just as we do today. Interestingly, the early concepts of Pare to address lower limb weakness and paralysis resemble the modern day endeavors of prepreg laminations to address the same presentations (Figure 6). Although Pare did not have access to these aerospace materials, he did not let that stop the conceptual thought process. Similarly, the professionals who followed him continued to fine-tune prosthetic devices and fitting techniques, at times getting a boost from 20th century industrial advances. Rising numbers of amputees during wartime also spurred growth in the prosthetic field and demand for new improved devices and

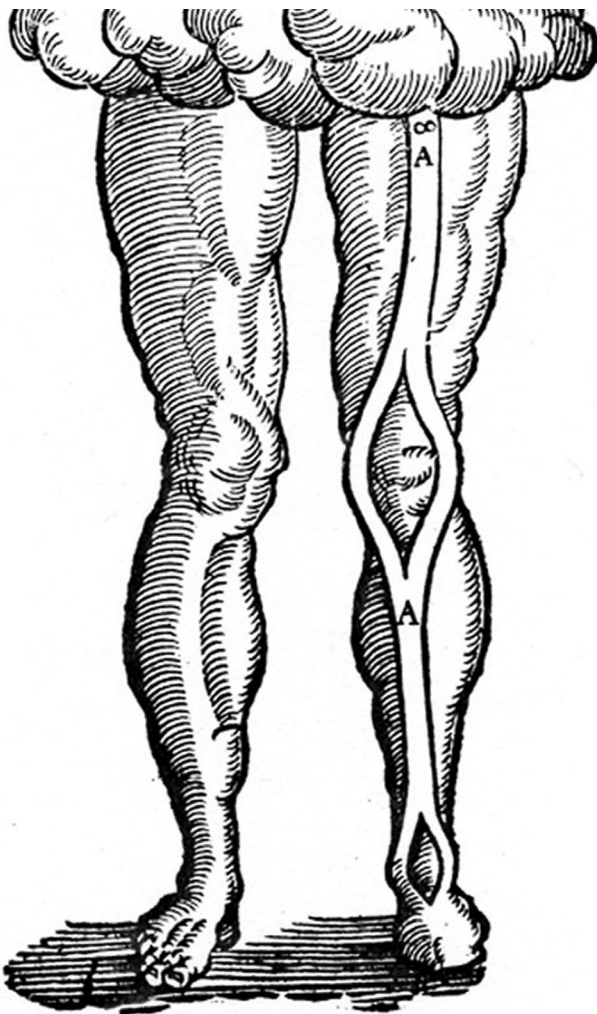


Figure 6. Ambrose Pare's orthotic design for dropfoot designed from linen (taken from his original line drawing on the topic – 16th century).

sockets. With the emergence of transparent plastics and thermoplastics for intimate contouring, the dreams of our prosthetic pioneers are within reach.

As material science advanced the upper limb prosthetist was able to return to fitting challenges with new ideas. Socket design advanced almost simultaneously with material science. One such patient population to benefit has been the individual presenting with shoulder disarticulation level limb loss. Case in point—a continuous socket design (Figure 7) allows for the introduction of effective lateral loading of the thorax by connecting bilateral shoulder. The patient reports several significant benefits with this design in contrast to previous discontinuous frame designs. These include easier donning and doffing secondary to a significantly more stable structure, an appreciable increase in ease of inhalation with the elimination of anteroposterior harnessing, and a reduction of the patients perceived weight by at least one-half that of the discontinuous shoulder frames. This flexible yet structurally sound socket design was not possible until our understanding of composite science allowed such conception and execution.

As always in times of great scientific innovation and experimentation, the challenge is to capture those concepts for posterity and to share ongoing discoveries with other professionals in the field so that all may benefit and the pace of improvement is accelerated. Currently, the entire field of Orthotics and Prosthetics suffers from a lack of written documentation. This puts current and emerging advancements at risk. Often, significant breakthroughs arise from the insights a professional gains from others. Spoken history can be lost for good, whereas written history endures to inspire future generations, who may, like us, return to the same challenges with new technology and materials at their disposal. The American Academy of Orthotists and Prosthetists Upper Limb Prosthetic Society is newly committed to enhancing communication between all upper limb specialists. This synergy promises to nurture further advances, perhaps helping today's upper limb professionals accomplish in a decade or two what took previous generations a century to realize.

As we push the specialty of upper limb prosthetics forward, perspective is important. We must remember who came before us—for both respect and knowledge. Words of a 12th century theologian and author come to mind. This phrase is often associated with Sir Isaac Newton in a letter he wrote in 1676. Interestingly the phrase goes back even further to John of Salisbury who was known to further his work through a significant knowledge of what was done previously.

"We are like dwarfs sitting on the shoulders of giants. We see more, and things that are more distant, than they did, not because our sight is superior or because we are taller than they, but because they raise us up, and by their great stature add to ours."⁵⁰

ACKNOWLEDGMENTS

The author thank the following individuals: Terry Supan, CPO, FAAOP, FISPO, for his influence and sharing of his upper limb

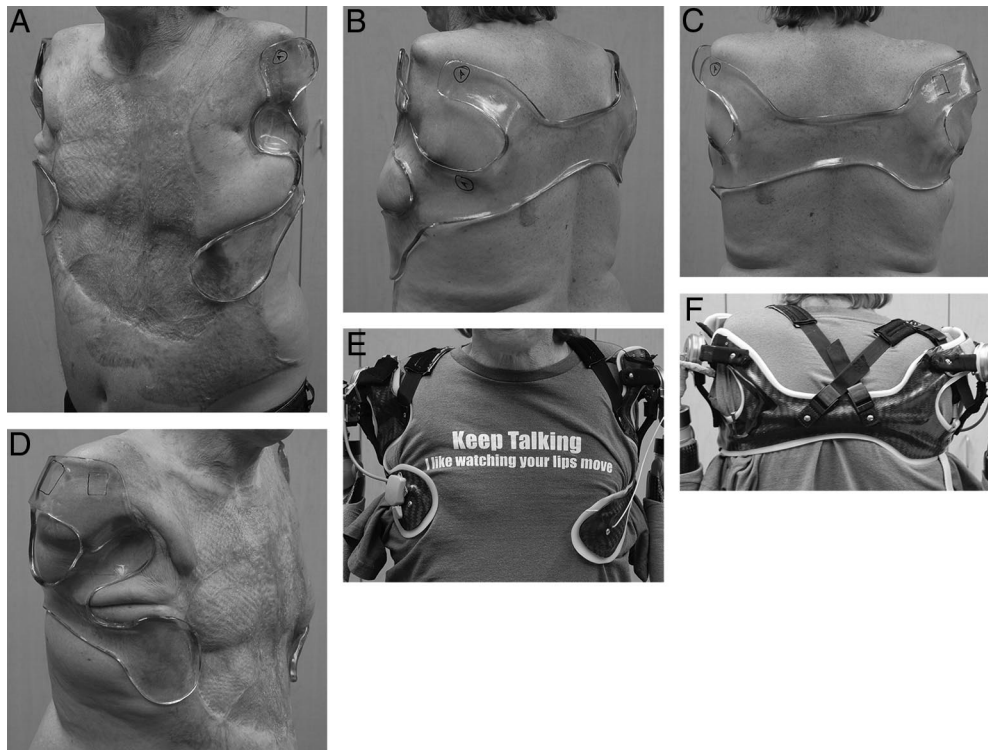


Figure 7. Bilateral shoulder limb loss secondary to electrical burn. A–D, Durr-plex frames indicating socket margins and FSR (touchpad). E and F, Continuous carbon composite shoulder frames.

knowledge during my prosthetic residency at Southern Illinois University in 1995–96; Tom Andrew, CP, FAAOP, for introducing me to more progressive thoughts in the treatment of individuals with upper limb loss during my attendance of the 1997 Utah Arm Course; John Miguelez, CP, FAAOP, for his ongoing friendship and clinical mentorship since 1998; Randy Alley, CP, FAAOP, for his passion for the biomechanics and his questioning why we do what we do, which ultimately makes us better clinicians. The author is grateful to Julie Lake for her literary review and editing.

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