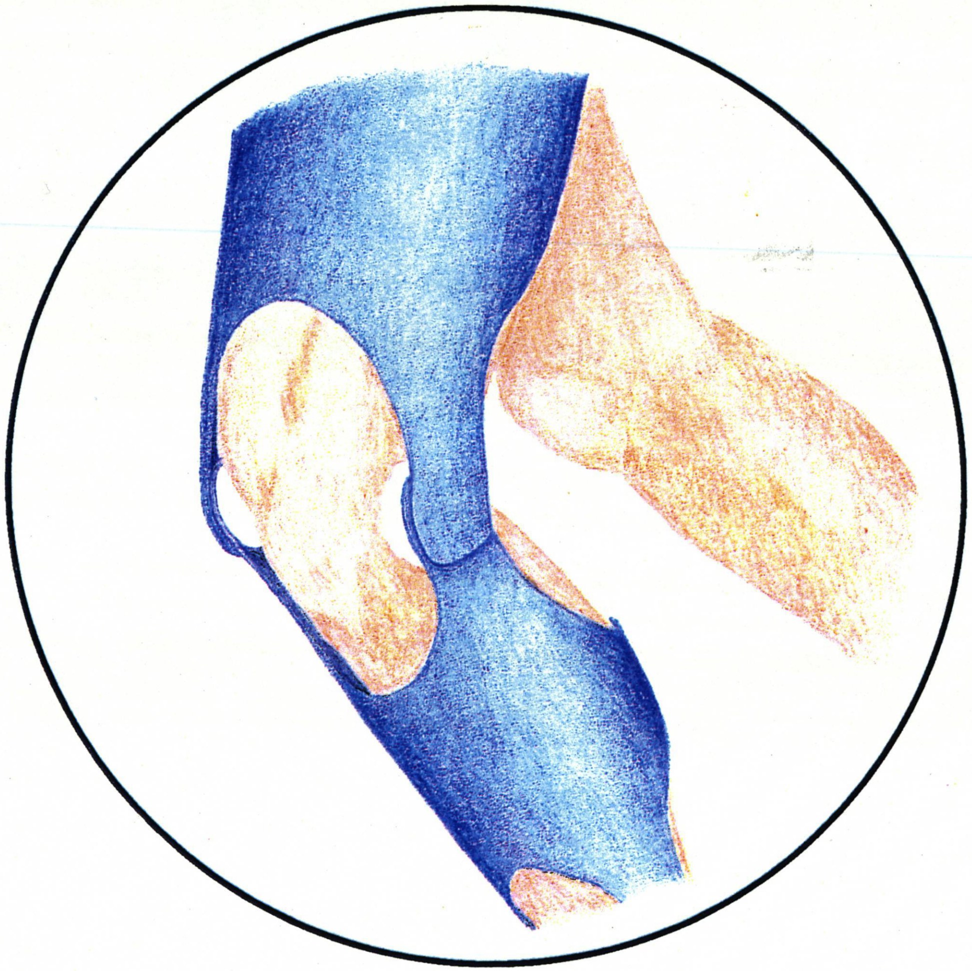
NATURAL CRUCH



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in

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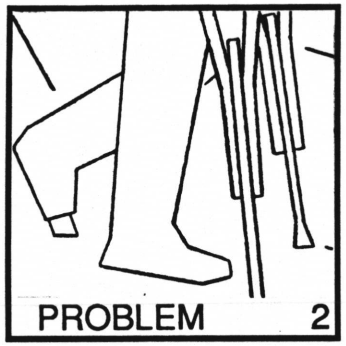

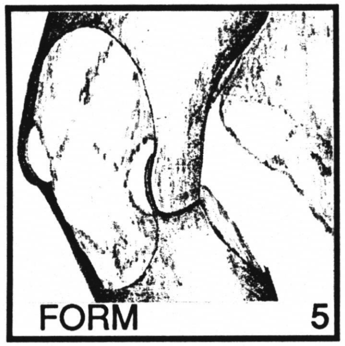

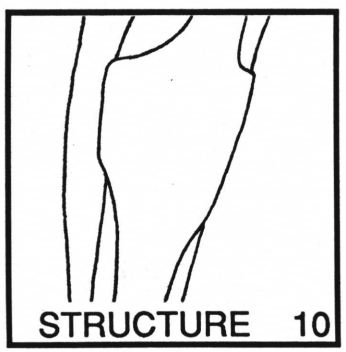

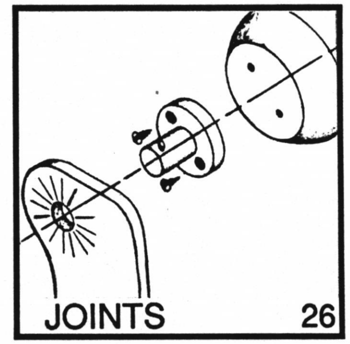

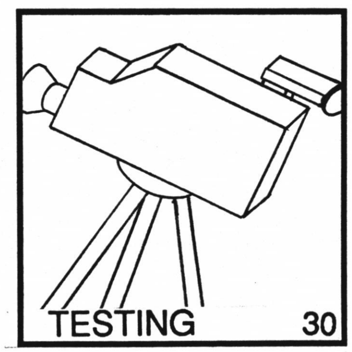

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INTRODUCTION

The proposed "natural crutch" provides ambulation assistance without the problems associated with arm-supported crutches. The new crutch has an exoskeleton structure which surrounds the disabled leg and carries the user's body weight while walking and standing. The load is transferred from the exoskeleton to the trunk of the body through a harness which lifts the pelvis on the impaired side. The intention is to simulate the internal skeleton's natural load distribution while compensating for the impairment.

Exoskeleton structures have been used throughout the 20th century to provide support for lower limb deformities [1]. Casts formed from plaster, plastic, and plastic with steel frames have helped to provide proper alignment and compensate for specific areas of weakness. These orthotic devices require custom fitting for the individual user and are prosthetic in appearance. Short of full leg length hip casts (which cannot be removed each day), no exoskeleton products found to date are designed to completely eliminate the load carried by the impaired leg. Cases with this requirement are generally fitted with some type of arm-supported crutch.

The natural crutch design is presented as an adjustable product which can be manufactured and then distributed to a variety of users. A proposal for a marketable prototype is introduced as a starting point for the new crutch design. Results of a full scale simulator test are used to determine areas requiring further development. All aspects of design attempt to include both engineering and industrial design perspectives. Before the design can be discussed, a formal problem definition and objective must be outlined. These are presented in the following sections.

PROBLEM DEFINITION

Assistive devices similar to the arm-supported crutch have been in use for over 4500 years [2]. Is the design so evolved that it cannot be improved? Attempts to do so have barely altered the original support structure. Within the past century engineers have produced alternatives to the conventional crutch design. Elbow crutches were introduced along with crutches with rolling tip surfaces, shock absorbers, and even gadgets that assist the user to a standing position. The large array of variations has yet to develop a truly unique solution.

Crutch-assisted ambulation is physically difficult and requires a high energy output from the user. The effort involved has been equated to moderate-to-heavy work such as jogging or running [3]. There are many problems contributing to the high energy cost including excess motion of the user's body (in the vertical direction) and of the crutches (in the lateral direction [4]). The gait is discontinuous and the crutch tip can send a shock to the user as it strikes the ground. However, the largest energy factor may be that the arms are used to support a load greater than they are intended to support. Figure 1 shows a disabled user on conventional crutches.

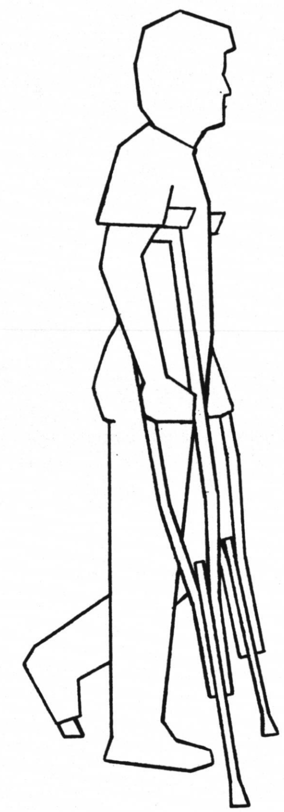
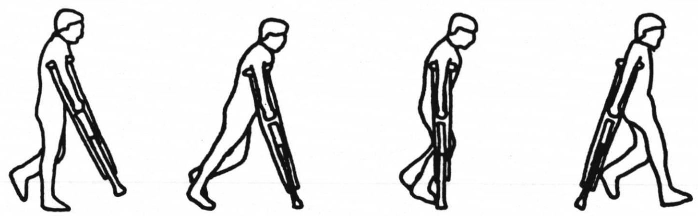


Figure 1. Conventional Crutches

Crutches send the load naturally taken by one side of the pelvic girdle up to the pectoral girdle. This distribution of force causes an imbalance between the forces on the impaired side of the body and those on the unassisted side.

In the first stage of a swing-through crutch gait the body weight is carried by the nonimpaired leg. The second stage transfers the weight to the arms as the body swings through the crutches [6]. See Figure 2 below.



Stage one Stage two

Figure 2. Stages of Swing-through Gait

The force carried by the leg in stage one is carried to only one side of the pelvis. Over time this one sided force can tilt the pelvis and sacrum, forcing the spine to compensate (Figure 3).

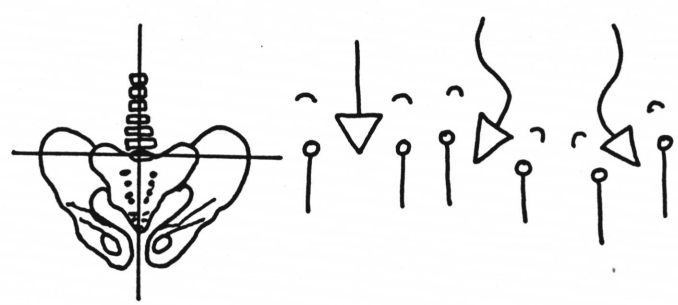


Figure 3. Spinal Compensation for a Tilted Sacrum

When muscle patterns develop to support the tilted structure, the spine can become permanently deformed [7].

The second stage carries the body weight through the arms and transfers it up to the pectoral girdle. Arms are not intended to carry such a large load and several problems can develop. Once problems arise, it's common for the user to rest the crutches under the arms to avoid damaging the arms further. This area is very delicate and large forces can cause more damage. Common pathologies related to crutch use include stress fractures, nerve damage, joint degeneration, aneurism and blood clots [8,9,10].

The cumbersome nature of crutches introduces additional concerns:

1. The swing motion increases the chances of catching on obstacles in the path.
2. There is a possibility of slipping on impact of the crutch tip.
3. The appearance is prosthetic and aesthetically impersonal.
4. The user must find out-of-the-way storage at each destination.

Perhaps the most debilitating factor of crutch ambulation is the occupation of the user's arms. There is no way to carry objects or work with the hands while using crutches.

Possible harm to the user along with the many difficulties associated with conventional crutches indicate a need for an improved design. The natural crutch project seeks to investigate a new solution while retaining the attributes of arm-supported devices.

OBJECTIVE

The objective of the natural crutch is to eliminate the problems encountered with arm-supported crutches by developing a device which compensates for the impaired leg and follows the natural biomechanics of the skeletal system.

The initial design objective is to provide an assistive device for the most extreme case of disibilty: a leg which cannot handle any load and must be completely supported and protected. From this product future developments can account for variations in the user's abilities. A specialized crutch may be required for each different type of disability.

<u>Design Criteria</u>

1. Provide Proper Load Distribution
The new crutch should carry the load usually taken by the disabled limb. The force needs to load the pelvis the same way the femur would transfer the force; allowing the trunk of the body to balance on each side while walking or standing.

2. Easy to Use
The crutch should be easy to put on and take off without assistance. It should also allow the user accessibility to the environment including the ability to stand, walk, sit, and climb stairs.

3. Easy to Maintain
The crutch should be easy to clean, adjust, and require few repairs.

4. Aesthetically Desirable
The appearance should be complementary to the user (just as a good pair of eyeglasses complement an individual's image).

5. Provide a Continuous Gait
Ambulation should not require excess energy output from the user. A continuous gait alleviates energy wasted by vertical body mass fluctuations, striking the ground hard, and excess motion of the assistive device.

6. Easy to Manufacture
Conventional crutches are adjustable, easy to manufacture, and inexpensive (approximately $50 per pair [11]). The new crutch must maintain a simple, adjustable design to compete for the same market.

7. Safe and Reliable
The user must feel adequately supported at all times. All wear on parts should be measurable and correctable for continuous performance.

AESTHETIC CONSIDERATIONS

One additional objective of the "natural crutch" is to remove any prosthetic, intimidating appearance. Assistive devices like crutches become part of the user's personality. This project will attempt to present a piece of apparatus which is pleasing to look at; not prosthetic.

An optimal design situation covering all of the objectives will involve input from many different perspectives. Unfortunately, the separate worlds of industrial design and engineering have difficulty working with one another.

This separation of design schools was not always the case. Prior to the Italian Renaissance, apprenticeship in the building crafts was used to train architects (industrial design as it has been referred to in this paper falls under the school of architecture). This developed practical engineering knowledge with an understanding of what arrangements would work and what would not work. Then the Renaissance drew architects into a revolution in the world of art where a theoretical approach became the popular attitude. This separated the architects from the craftsmen and specialized the fields of architecture and engineering. By the eighteenth century, educational institutions were developed to instruct the engineers and architects in different schools [12].

High quality products are developed from integrating the best of both worlds. Examples of this team approach are seen today in the automobile industry. Top of the line vehicles such as Lamborgini, Porsche, and Jaguar are the results of design teams working for both form and function.

Formally (in the architectural sense), the concept which the crutch design will follow is this:

If an object is designed with a complete understanding of it's function, it will be formally exceptional.

This concept can be seen with the design of high technology sports equipment. Over the years technology has developed a high level understanding of the equipment's purpose. For instance, the modern golf club is an aesthetic wonder. Decades of evolution have refined the understanding of it's function and developed an excellent piece of equipment.

The best examples of highly evolved design and it's formal consequences are seen in nature. Animal and plant life forms are evolved with a complete understanding of function and environmental interaction. Life forms of any type demonstrate architectural excellence.

One reason for poor development of assistive devices in the past is the public idea that they are charity. The stereotype of the handicapped being given charitable help accompanies the idea that "beggars can't be choosers." Today, things are changing with a growing conscience of the rights of the disabled. As the disabled achieve more rights, the devices made for them will be chosen, not given charitably. Manufacturers will need to apply normal marketing strategies. This includes developing quality products which are appealing to their consumers.

Designers will need to understand the perspective of the disabled user. As one engineer says "devices become an extension of the user's self-perception [13]." An able-bodied person gets an understanding of this when they are choosing frames for eyeglasses. They spend a great deal of time with this decision because eyeglasses have such a large impression on their self-image.

Since the purpose of the natural crutch is to augment the user's leg, the design is based on complementing the human form. The crutch must supply external support and therefore is controlled by the outside surface of the leg. It can be viewed as a projection of the surface area of the leg, foot, and hip regions. This relationship between user and assistive device is very similar to a piece of clothing. An ideal solution might be similar to a pair of pants; simply pulled on over a leg which requires assistance.

The crutch assists the user in interacting with his or her environment. The person's actions within the environment (walking, standing, sitting, etc.) as well as the environments affects on the apparatus, must be taken into consideration. These effects may include wear on parts, pathway obstructions, and social interactions. Focusing on just the apparatus would not provide the overall picture of the user-apparatus-environment interaction.

THE USER

The natural crutch could be worn by many people who have the capabilities and need to use it. There are several abilities which are required of a person when using the new design. These include:

— A strong sense of balance - walking requires feedback from the legs and feet to help balance and propel forward. This feedback is reduced while wearing the crutch.

— An unimpaired leg capable of walking - only one leg can wear the crutch; the other must walk normally.

— The ability to propel the impaired leg forward - this can be done either by muscular contraction or by rotating the body.

— The ability to withstand contact points of the crutch - the crutch must center itself on the leg with supports; the axial forces should be minimal.

The new design should be able to help those who are unable to apply pressure to one of their legs. This may include user's with short term disabilities such as broken bones, severe strains, or surgical recuperation. It may also assist those with chronic conditions such as permanent injuries, minor deformities, or aggravated joints. In the future the design principle may be adapted to assist those with less severe impairments.

The Permanently Disabled User

This section investigates what knowledge is available about the permanently disabled populations which might use the natural crutch. The disabled population in America is constantly changing in number. Due to the amount of information needed to describe any single person's limitations, it is difficult to get accurate data on any large scale. Accounting for health conditions, functional abilities, and demographic information makes it more impossible still. Even if this information could be compiled accurately, it would be obsolete before it could be used.

Market research and political polling are the primary resources of information on a national level. Neither of these reach out to collect data on the disabled public. There are some groups attempting to assemble a database of the physically and mentally limited [14]. These include the:

National Center for Health Statistics
Social Security Administration
(they have statistics on certain groups who receive income through the SSA, it is not a good cross-section)
Bureau of the Census
Rehabilitation Services Agency.

Data collected by these groups is coordinated and published by other organizations such as the:

Committee on Demographic Statistics
National Institute for Disability and Rehabilitation Research
Presidents Committee on the Employment of People with Disabilities.

These organizations were able to conduct surveys through the 70's and early 80's on topics associated with disabilities. Since that time, federal cutbacks have strongly limited the ability to collect, sort, and distribute information. This investigation will have to rely on statistics up to 20 years old.

The Congressional Research Service surveyed Americans in 1976 and 1977 to measure the prevalence of certain types of impairments. Those permanently disabled which might use the natural crutch would be found in the lower extremity handicap category. These are listed below in Table 1 [14].

All surveys referred to in this discussion did not include institutionalized people. This implies that all people in hospitals, nursing homes, etc. are not included in the data. A significant percentage of the handicapped population may be left out due to this practice.

The National Institute on Disability and Rehabilitation Research conducted surveys from 1983 - 1985. The average of the results for those years found that 45.2 people out of every 1000 have an impairment of the lower extremities [15].

It is quite difficult to find information which gives any indication of severity of impairments, or functional abilities. This information is needed by designers in the rehabilitation field to understand user's abilities. These factors will be taken into account as the designing and marketing of rehabilitation devices change.

There is an additional area to address when considering the user. The actual number of people taking advantage of rehabilitation technology is very low. In 1972 the Social Security Administration study reported only 25% of handicapped ages 16 to 64 had any type of rehabilitation. A 1980 Census Bureau study in Richmond found this number to only be 16% [13]. Possible reasons for such limited use could be:

- they may not see any possible benefit from rehabilitation
- those receiving compensation want their condition to appear as bad as possible
- finances - not much money is allocated for rehabilitation assistance
- they may have difficulty getting transportation to services
- many physicians do not encourage rehabilitation.

Once the disabled population is educated about the benefits of rehabilitation and assistive devices, the market will grow to meet their needs.

Table 1. Findings of the Congressional Research Service

Impairment: Lower Extremity Handicap	Age: All	<17	17-44	45-64	65+
Total	7147	1124	2491	1914	1618
Male	3643	634	1466	951	592
Female	3503	490	1025	963	1025

All numbers are in thousands of persons

EXOSKELETON DESIGN

The new crutch design follows the natural model provided by the internal skeleton. It applies a balancing force to the pelvis on the side of the impaired leg. The hip and buttock regions are suspended by a harness delivering a force up through the trunk, replacing the load normally applied by the leg.

The harness is supported by the exoskeleton structure surrounding the impaired leg. The structure extends below the foot and secures the shoe. The leg is suspended in the exoskeleton and the load is carried up the outside shell; bypassing the impairment.

The overall shape of the exoskeleton shell is an extension of the leg's surface. It's structure is based on sequencing strong vertical members on opposite sides of the leg to carry the load. These pieces together compose a steel frame capable of carrying the user's body weight.

The steel members are held in place by thermoplastic sheets molded to the shape of the leg. One eighth inch sheets of North Coast Medical Clinic thermoplastic stand up to 185 psi [16]. Once the plastic is heated to 150 degrees F in a hot water bath, the sheet is easily formed to the desired shape. One general shape should fit a wide range of sizes; there should be no need for custom shaping. Upon cooling the plastic regains it's rigidity while remaining in the molded position.

If needed, higher strength thermoplastics are available from medical equipment suppliers. The stronger the plastic, the higher the required molding temperature.

Each of the pieces for the crutch design are presented in this section. Dimensions for the components are not specified as they may change with future developments. The appendix contains calculations for determining many of the component dimensions. Spreadsheets showing possible dimensions are set up to change along with the design specifications.

Before the individual pieces of the exoskeleton were determined, the overall look of the crutch on the leg was investigated. It is this complete picture which determines how the user is perceived when wearing the device. The design process is continued by attempting to match the desired image with a functional set of components. This procedure partially compromises the premise of developing a good design by completely understanding the crutch's function. As the design evolves, a better understanding of the function can be integrated into the process. Eventually through iteration, the ideal statement "If an object is designed with a complete understanding of it's function, it will be formally exceptional" can be realized.

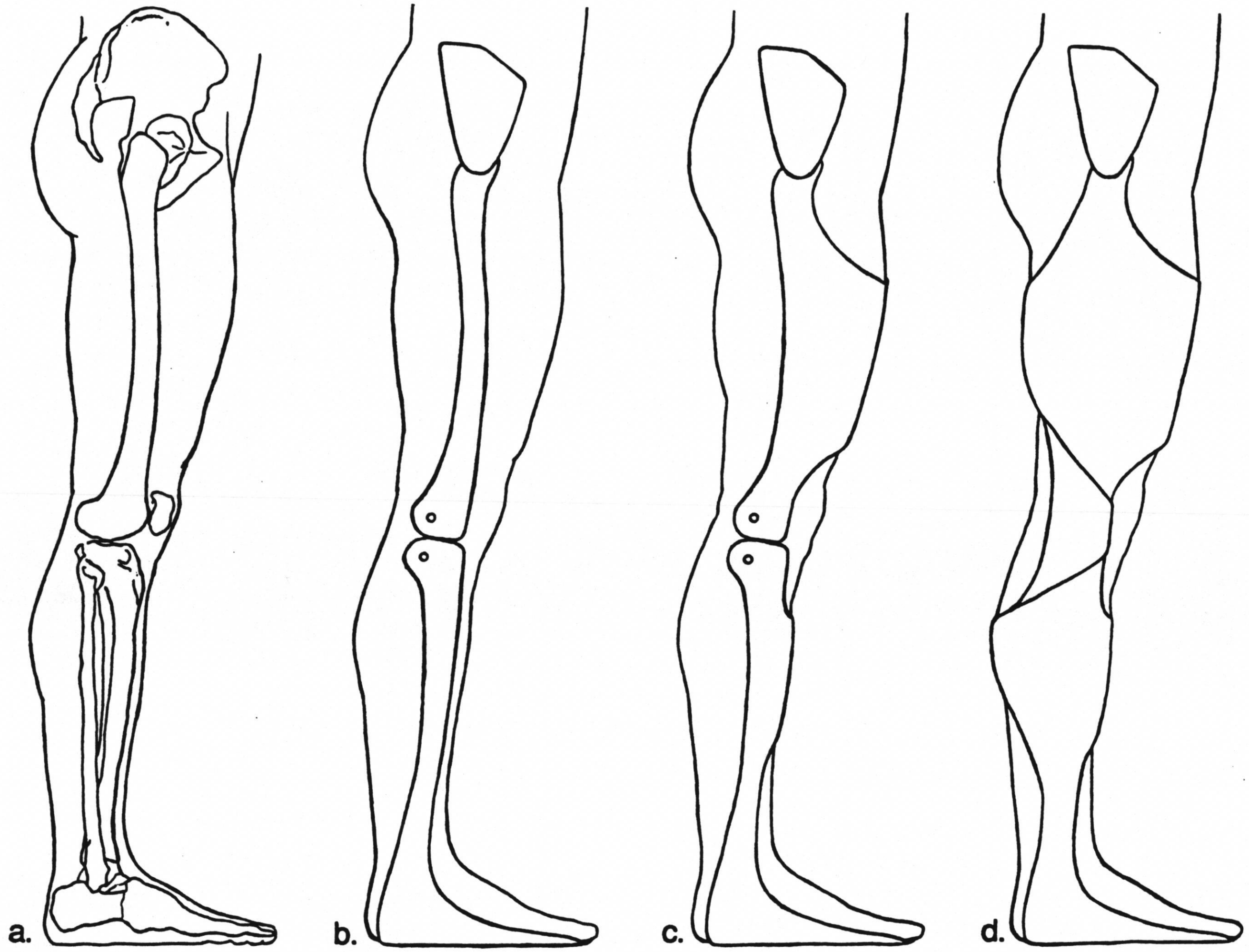


Figure 4. Original Exoskeleton Progression

The conceptual drawings of the natural crutch as an extension of the leg's surface are shown here in Figure 4. The internal skeleton of Figure 4a provides a model for a strong support configuration. Vertical members of the natural crutch were based on the internal model to simulate the skeleton's purpose and strength. This is seen in Figure 4b as the shapes of the supports follow the shapes of the pelvis, femur and tibia. The two points of rotation at the knee correspond to the rotation centers of the femur and tibia when the knee flexes.

The third drawing includes the anterior section of the shell. The thermoplastic pieces form a unit with the steel frame which can be easily placed on the leg. Posterior thermoplastic pieces can then be snapped into place on the thigh and calf areas to secure the exoskeleton. Shown here in figure 4d along with a cover for the knee joint area.

These ideas were applied to building a steel frame which contributed to testing the natural crutch concept. This frame was useful in altering the concepts to a new proposal for a workable design. The following sections discuss each piece of the proposed design and explain their contributions to the overall crutch. A more in depth look at the testing frame is offered following the descriptions of the crutch components.

Lower Leg Support

The base of the support structure must be solid enough to withstand the motion of the walking gait and the weight of the user's body. This is especially the case at the foundation because any instability will be passed on to the upper frame and magnified (the upper support is secured by it's attachment to the lower support). Therefore, a single unit is used to encompass the ankle and foot region.

Figure 5 illustrates the U-shaped metal piece which surrounds the shoe and lower end of the user's leg. Ideally, one part would continue from the inside of the knee joint all the way around to the outside of the joint. It would need to measure exactly the correct length for the user and this would be quite an expensive arrangement; requiring either a custom fit or a very wide range of available sizes. Since this is not economically viable, the frame is divided into three units to provide adjustable lengths. The lower U-shaped base, and two extensions which continue up to the knee joint.

The interface between the U-shaped base and the extensions must provide adjustment in small intervals for an accurate fit. Several options were considered for a sliding type of arrangement; where a shorter lower leg would have the pieces fit closer together and a longer leg could extend them farther apart.

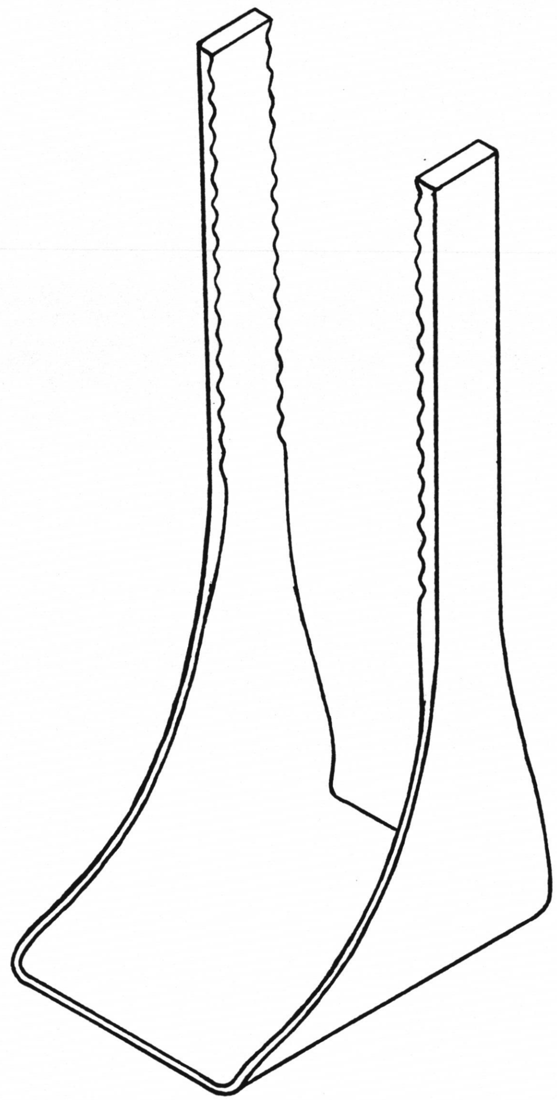


Figure 5. Lower Leg Support

The interface chosen for the crutch is a simple series of interlocking grooves on each of the frame units. The ridges provide a small unit of adjustment, allowing a precise fit.

One drawback of this shape is the manufacturability. The shape could be cut and milled from sheet metal but it would be very difficult due to the thickness difference between the upper and lower regions. This thickness would not be necessary through the lower section around the foot. The additional steel would only add weight and bulk to the crutch. The best option may be to cast the part or weld pieces together.

The shapes of the curves through the lower region attempt to minimize the perceived size of the metal unit. The curves are continuous with no sharp angles to roughen the appearance. The shape follows the taper of the foot at the front and the angle of the heel towards the rear. Rounded edges are used at the 90 degree bend between the base and the uprights (each of the crutch components attempts to follow the smooth curves of the human form).

One of the alternatives considered interlocks rectangular units from the upper extension and corresponding openings on the flanged sides of the lower piece; shown here in Figure 6a. The cavities continue farther back along the x axis than the rectangles so that the back of the base comes in contact with the extension. With an applied load securing the pieces together, friction can also be used to keep them in place. This configuration is more complicated than the ridges and it does not adjust with the same precision. If the rectangles are made small for greater precision, then they can be easily damaged. This arrangement also exposes rough edges where the two steel members don't overlap.

Figure 6b illustrates an additional option for the lower frame structure. It involves drilling sequences of holes in adjoining pieces then bolting or riveting the units together at the appropriate length. With an applied preload, this option also makes use of friction. However, the many holes required for adjustability will weaken the frame and expose a nonattractive surface when it is in an extended position. Also, if rivets are used it will be difficult to adjust the crutch for a different size.

Note: When choosing a fastener which will receive a shear load, a heat expanded rivet is preferable to a bolt. The rivet expands to completely fill the hole; providing a more even distribution of force than a bolt-type connection [17].

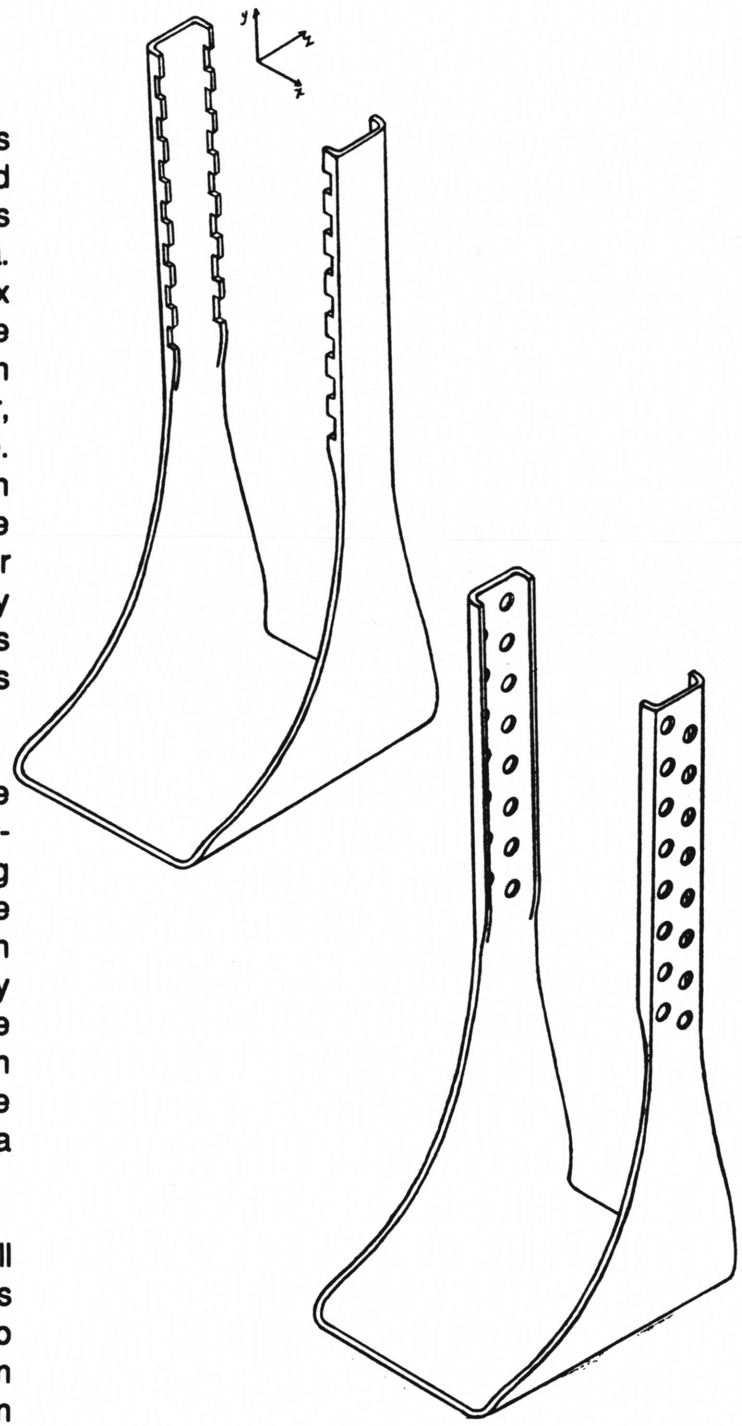


Figure 6. Lower Leg Support Alternatives

The unit of adjustment will also be a problem. The closer the holes are together, the weaker the length will be where no overlap occurs. If the size of the holes is increased, this also weakens the structure; though large diameters are necessary to increase the resistance to shear.

Friction alone was also considered as an option between the adjustable parts. The nature of walking sends a repetitive shock-type force up through the axis between the pieces. This could possibly jolt the connection; weakening the structure.

One advantage for all of the alternatives for this piece is that they are designed to be cut from a uniform piece of sheet metal.

The interlocking grooves provide the simplest solution without the aesthetic, adjustability, and strength problems caused by the other options.

Extension Pieces

The interlocking extension pieces for the U-shaped base continue up to the knee joint. Figure 7 is a front, side, and back view of the right side lower leg piece. A matching piece is used for the left side with the ridges on the opposite side. The piece is thicker where there are ridges than at the flat section leading to the joint. As the thickness narrows, the width of the shape increases to maintain a strong cross section.

Surrounding the hole for the joint is a circular array of ridges to help lock the knee at the correct angle. The complicated textures and shapes for these pieces make casting the most viable means of production.

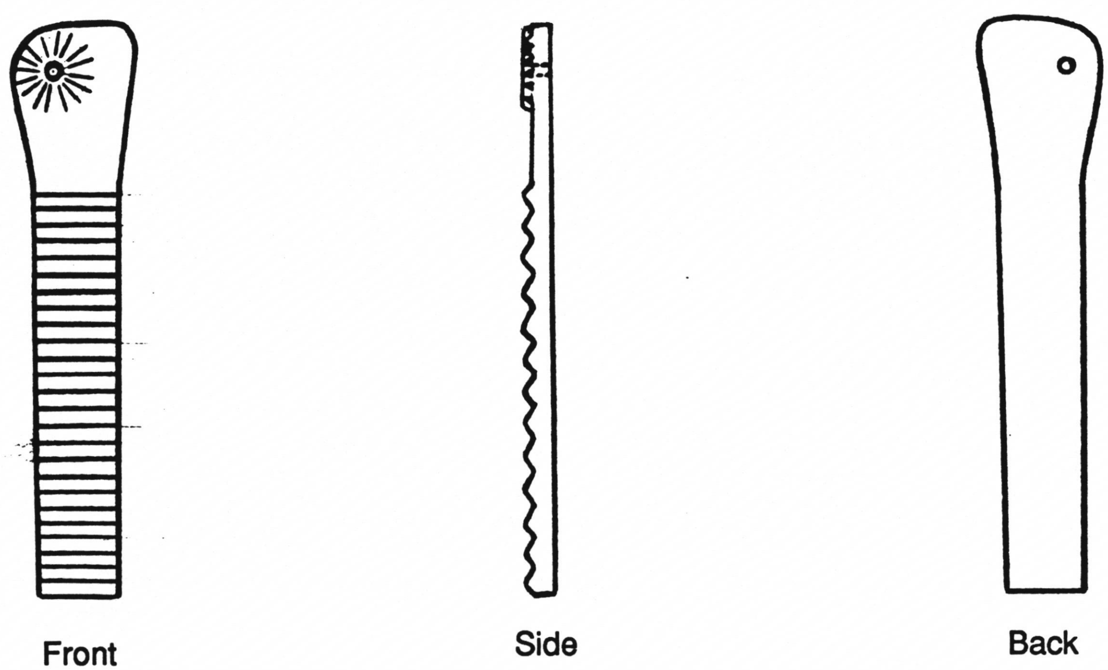
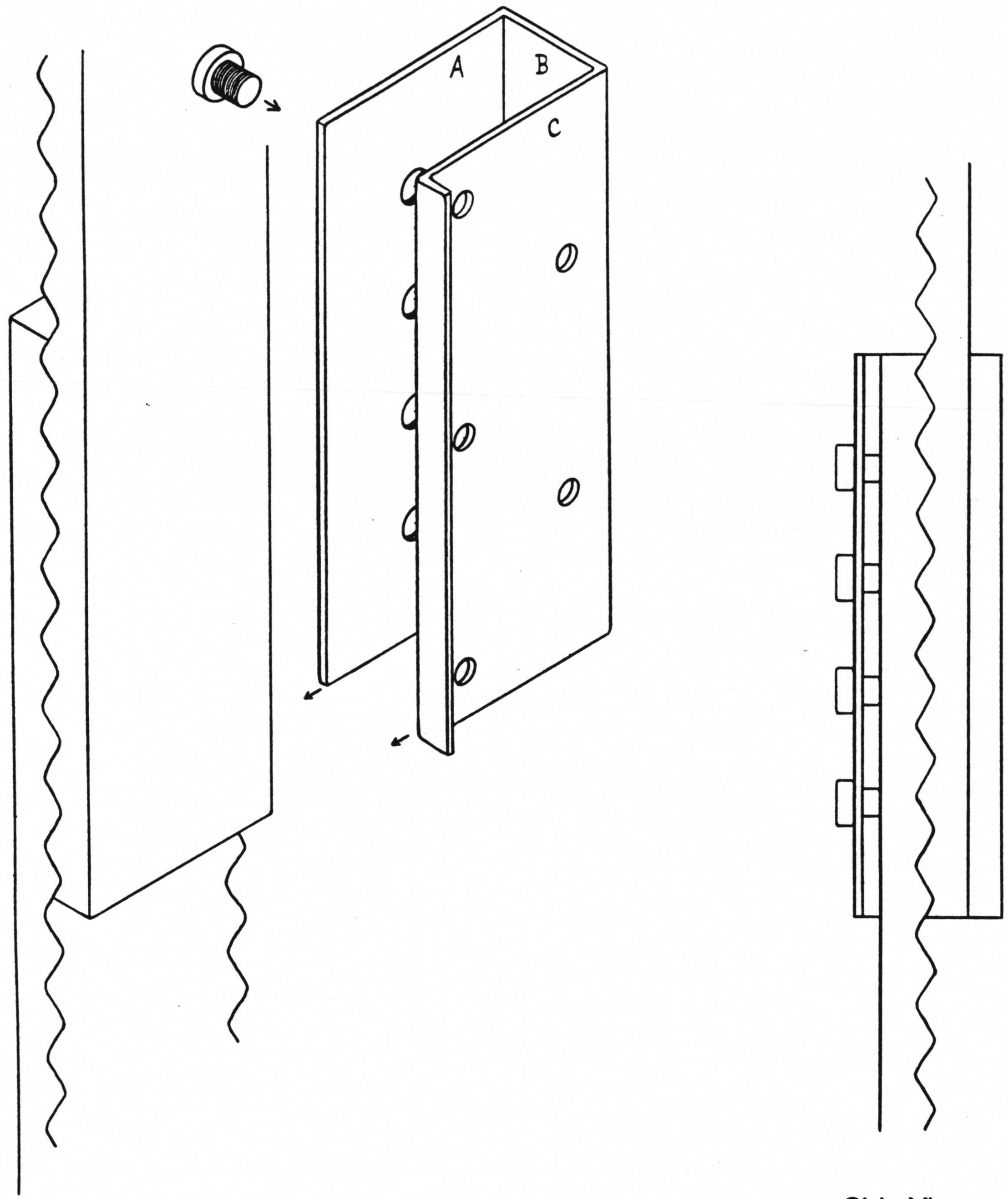


Figure 7. Right Side Lower Leg Extension

Securing Assembly



Exploded Isometric View

Side View

Figure 8. Securing Assembly

After the correct length for the lower leg section has been determined, the pieces must be secured together. This is accomplished with a three sided rectangular assembly which encompasses the front and sides of the overlapped frame section (Figure 8). Holes, drilled and tapped along the center line of plane A, are spaced 0.8 inches apart. Each hole is for a set screw which applies pressure to the unit and holds it together. A designated load can be applied at each screw to maintain a strong juncture. The set screws are relatively large in diameter, 3/16 of an inch, to provide a more even distribution of force.

Interlocking sections of the frame are designed to slide apart for a tall user and together for a shorter user. For this reason, the grooved lengths have been designed straight so the relative position between the knee and foot is not disrupted when different sizes are fitted. This linear section deviates from the conceptual drawing modelled after the curved internal skeleton.

For even the tallest person, an overlapping section must be maintained for stability between the upper and lower sections. The overlapping distance can be determined once the cross sectional dimensions are specified. The box shaped assembly can be secured on this interlocking segment.

Plastic Forms

The securing assembly is also used to connect the thermoplastic pieces which attach the left and right sides of the frame. The molded thermoplastic is riveted right onto plane C of the assembly (see Figure 9). Holes drilled for the rivets are laid out in a zig zag pattern. They are drilled so that the rivets are recessed on the inside of the rectangular shaft. The rivets then lie flush with the plate that the frame presses up against. This is needed to avoid uneven force distribution or twisting of the lower leg unit. One assembly on each side of the leg attaches the anterior thermoplastic shell in place.

Posterior thermoplastic pieces are also connected along the securing assembly. These sheets are riveted to a thin metal band which runs along the inside surface of the plastic from one side to the other. The metal band hinges on the securing box on the outside of the leg. Figure 9 shows the hinge and connecting metal band. They are welded together with enough space between the forms to let the rear form swing open freely. The hinge can also be welded right onto the securing assembly. This hinge allows the thermoplastic piece to remain attached to the crutch and still swing open for transfer in and out.

This way of fastening the plastic forms conceals the inner frame structure. The original image as developed in the conceptual drawings (Figure 4) is still maintained. The curve of the leg is expressed through the plastic covering.

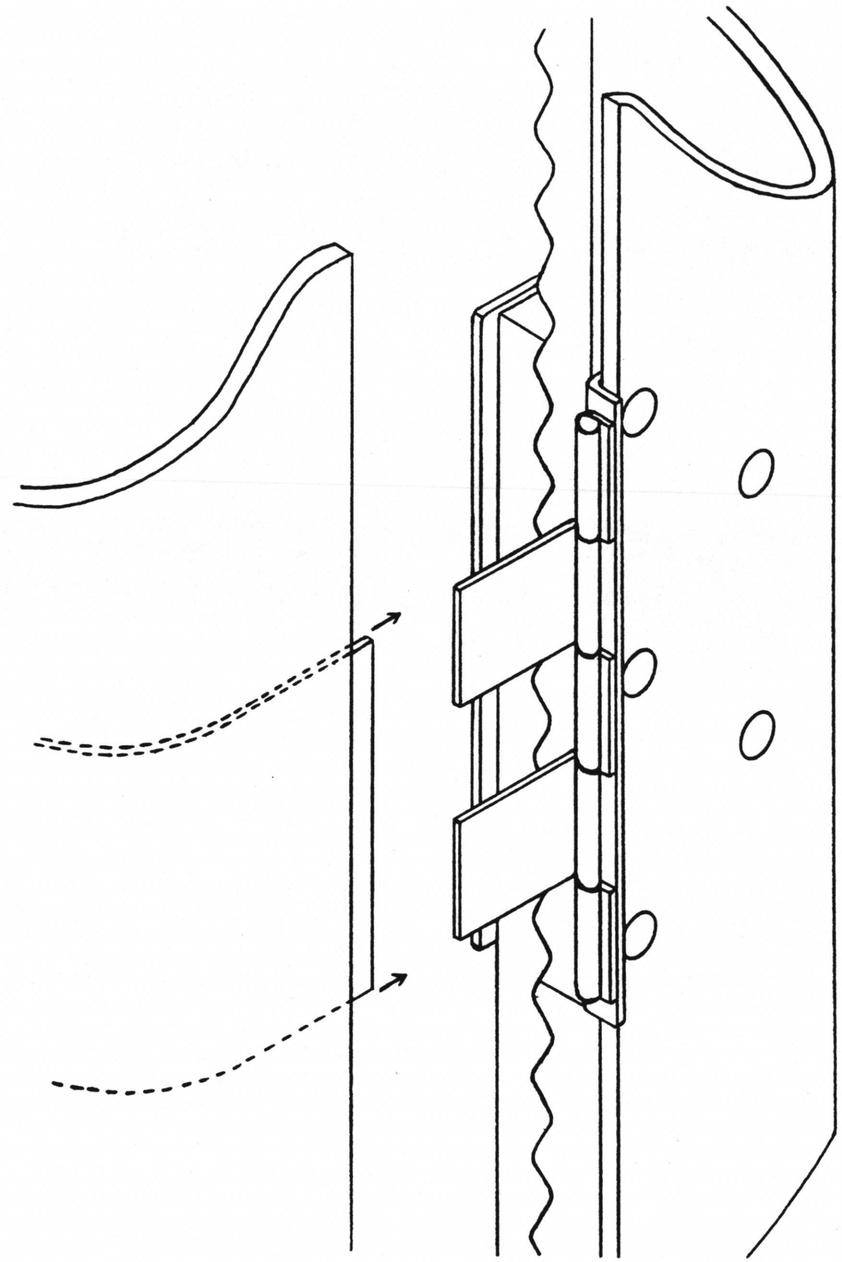


Figure 9. Hinge for Posterior Thermoplastic Form

The other side of the plastic form is connected to the assembly on the inside of the leg. It is attached with a clasp which the user can open when taking the crutch off. Shown here in Figure 10. It is located on the inside of the leg because this area is easier to reach than the outside of the leg.

The same lever based principle is used in many fastening situations. Tool chests, trunks, and ski bindings all make use of this arrangement. It is simple to open and close and it is difficult to accidentally unlock. Due to the scraping motion of the insides of the legs while walking, it may be best to design a lock for the clasp. The angle of the leg in the crutch should avoid any safety hazards if the fastener should open inadvertently, however, it may cause unforeseen problems.

Each thermoplastic sheet is lined with strips of velcro hooks (they are easily purchased with a peel away adhesive backing). Foam padding can then be velcroed in place to adjust the correct circumference size for each person. One quarter inch layers of padding each have strips of velcro loops on one side and hooks on the other. A user with a smaller leg can use several pieces of foam and vice versa (with only one layer of foam, the circumference is decreased by over 2 1/2 inches). The foam provides a comfortable interface and helps to center the crutch on the leg.

Choosing a color for the thermoplastic pieces is similar to deciding what color pants to wear. In this case, the pants (color) cannot be changed on a daily basis. This requires a color which is adaptable to different situations and moods.

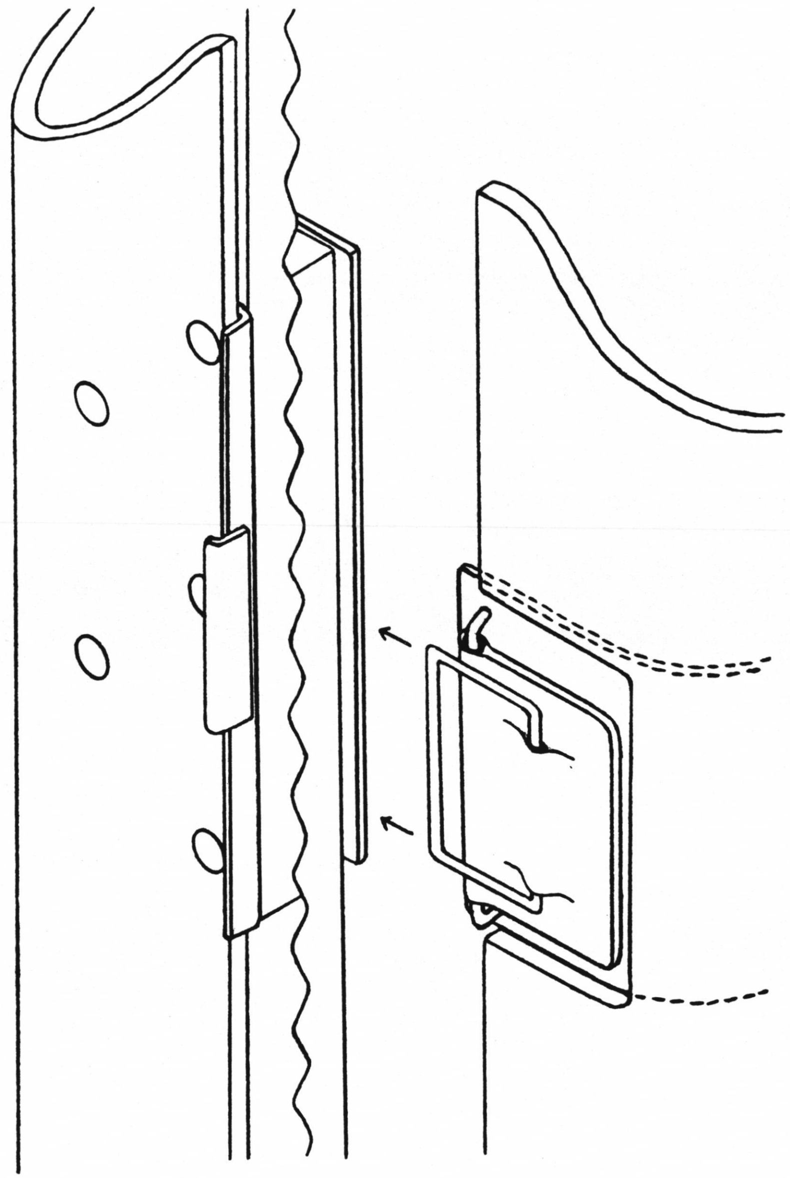


Figure 10. Fastener for Posterior Thermoplastic Form

It is assumed that a crutch user would not like to attract attention to the device. Attention to any garment can be minimalized by darkening the color. Black would be the best option for this purpose, however, it can be construed as morbid. Also, any color very different from the rest of the user's wardrobe will draw more attention because of the contrast. A dark blue color has been chosen for development of the natural crutch image. This image is seen on the tilte page. The versatility and popularity of the color is obvious from the wide use of "blue jeans" thoughout the population.

Securing the Shoe

The user's own shoe is used to provide correct positioning, foot support, and protection (provided the impairment does not restrict shoe wear). It can be secured right into the U-shaped frame; allowing the user some control over their appearance. Figure 11 demonstrates from the top view a set of clamps which adjust laterally to hold the sole of the shoe. The clamps press in sideways and lock into a soft sole with a sharply knurled edge.

Only shoes with certain characteristics will secure the crutch. The shoe must: have a cutout region at the arch, be soft enough to accept the clamps yet solid enough to maintain it's general shape, and the sole must have a base thick enough to hold the clamps. Most standard tennis shoes meet these requirements.

One clamp is rounded for the arch area and the other is tapered for the outside blade of the foot (this blade will have a slight angle outward for a normal stance). With two different screws in each clamp these angles can be adjusted to the individual shoe. The screws are held in place by the uprights of the U-shaped support. The heads of the screws lie flush with the outside of the support to make sure there is nothing to catch on obstacles in the path. They rotate but do not move forward or back. This causes the clamps which have tapped holes to extend forward or pull back along the lateral axis.

Another option to secure the shoe might be to permanently screw the sole of the shoe to the base. This would damage the shoe and make it difficult to readjust if a change is required.

The same problems occur if the base is threaded through the sole the way many orthotics are secured [18]. Soft soled shoes would be too difficult to cut the sole and position and hard soles would require an additional piece placed under the shoe. It would be necessary to customize a shoe each time a user was fitted, eliminating almost all temporary users.

Originally, the U-shaped base was designed to fit inside the shoe of the user. Though it would be difficult to fit a shoe around such a bulky frame it seemed to be the ideal solution. After attempts to walk with the testing frame with an under the heel support, it was discovered that the support must arise from the center of the foot. Within the shoe, the supports could only arise from under the heel (where the hole is cut out for the ankle). This configuration is similar to a person walking on their heels. The body is out of balance and the center must lean back to compensate.

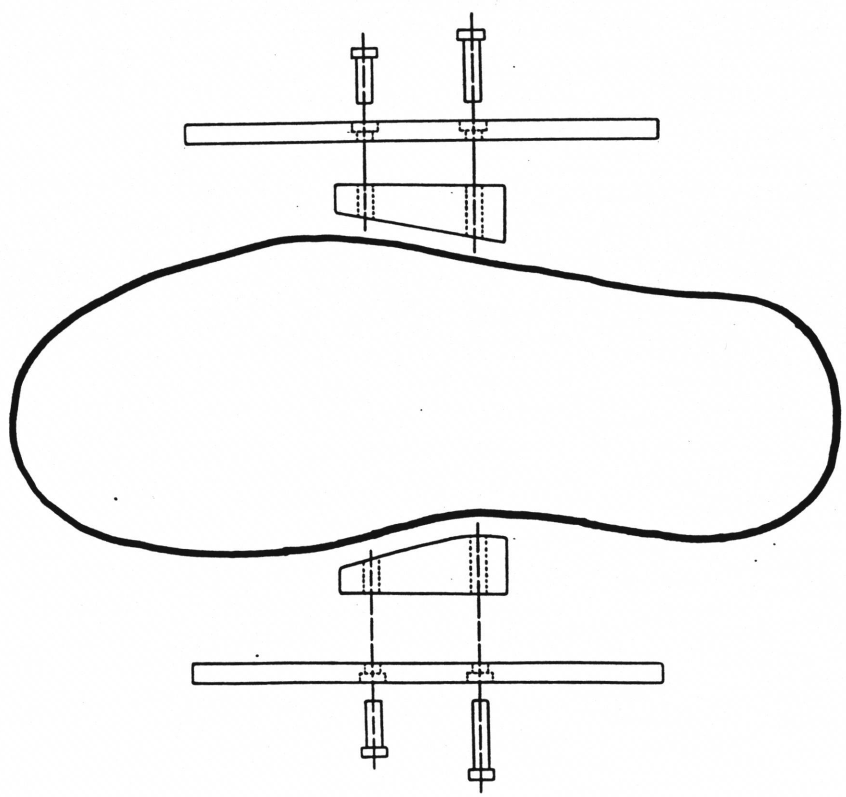


Figure 11. Clamps for Securing the Shoe

Rubber Sole

The flat metal base of the frame does not provide a comfortable walking surface. The metal would quickly wear away on the ground, make a clanking sound, and give a strong jolt up the exoskeleton as it strikes the ground. To avoid these problems a hard rubber sole is screwed onto the base of the frame (Figure 12).

Five holes are drilled in a cross pattern through the metal plate to secure all sections of the sole. The screws are dropped down through the steel and into the rubber. The flat screw heads are recessed until level with the plate surface to avoid interference with the shoe.

The dimensions of the rubber sole are one eighth of an inch shorter than the steel base on each of the four sides. This allows the frame to protect the unsecured edges so that they do not snag or open a gap.

A rounded surface allows a smooth rolling motion while stepping with the crutch. The hard rubber material acts as a shock absorber and a measurable wearing surface which can be easily replaced.

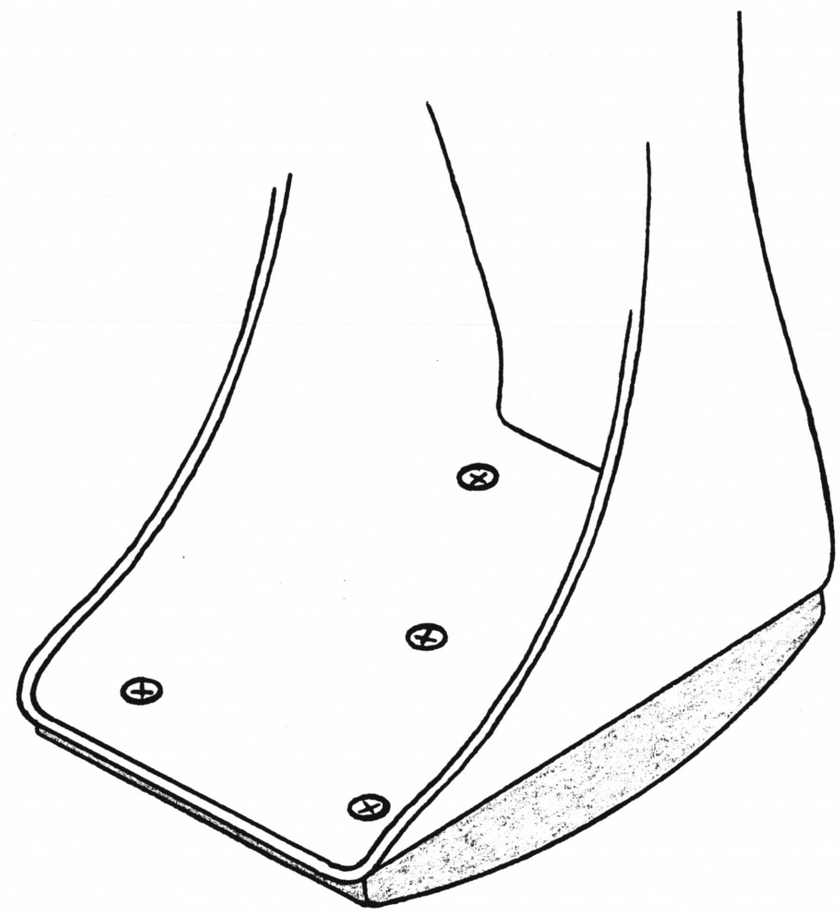


Figure 12. Hard Rubber Sole

Soles are available in variable thicknesses for users with different foot sizes. Those with a longer foot will require a higher sole to avoid rolling into the user's toes while walking.

It is suggested that a black colored rubber be used for the sole. Black does not attract attention the way lighter colors will and it can minimize the appearance of the base.

Upper Leg Support

The exoskeleton frame from the knee to the hip on the outside of the leg must transmit the entire weight of the body up to the hip piece. Figure 13 shows the long connection between the joints.

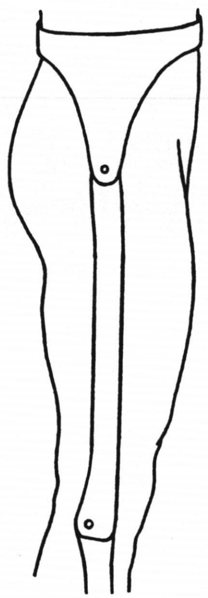


Figure 13. Upper Leg Frame Piece

Like the lower leg steel members, the thigh piece can incorporate adjustable sliding parts through the long straight region. The natural curve of the femur projection has been replaced with this straight region for adjustability. The straight lines present an artificial look which detracts from the natural curves of the human form. This is also the case through the lower leg region.

The thigh support can take advantage of the same interlocking ridge configuration used by the lower support. It also has the same thermoplastic requirements as the lower leg area.

Steel members carry the same general configuration with the width increasing as the thickness decreases. The grooves around the knee joint are located on the inner side. This is because the thigh member attaches on the outside of the knee to allow the additional space needed for the larger leg portion.

The upper section of the thigh support attaches on the inside of the hip piece. By arranging the frame in this way, the belt and hip piece help to secure the thigh support next to the body.

There are no sharp corners on the vertical support pieces. The ends have been rounded to visually flow into the next component (see the knee joint in Figure 13).

The lower end of the thigh suppport is slanted downward slightly. Figure 7 shows how the lower support at the knee joint is slightly angled upward. This assures that the anterior edge of the pieces will still overlap when the joint is held in a flexed postition. If they do not overlap, a gap occurs, breaking the continuous appearance of the exoskeleton shell. This problem could be solved by evenly rounding the support around the joint hole. This type of connection is pictured in Figure 13 at the hip joint. Notice, it is not as continuous as the knee segment. It may be best to incorporate a similar design at the hip region.

An important difference between the upper and lower regions is the diminishing space on the inside of the legs. The thighs grow closer together the farther up the leg the exoskeleton is located. For this reason, the inside thigh member is not adjustable. A single size support should provide the stability necessary for a wide range of sizes. The securing assembly can then be made thinner and secured up or down the piece depending on the length of the user's thigh.

Any fraction of the load travelling up the frame pieces of the inside of the leg must transfer to the outside thigh support. Where the inside thigh support stops, the securing assembly should transfer the load through the thermoplastic component over to the outside frame piece. If this configuration is not strong enough to carry the force, a metal band connected to each of the securing boxes on the thigh supports will handle the load (this is the case in the testing frame). The band can be attached underneath the plastic component without altering the crutch appearance.

Hip Piece

Originally, the frame piece next to the hip region was an external representation of the pelvis. The shape of the support resembling the side view of the iliac projection. Several options were considered to support the harness from the side of the body this way including the configuration in Figure 14. Testing, however, found the pull on the soft tissues inside the thigh to be very uncomfortable. A new way of suspending the harness was developed.

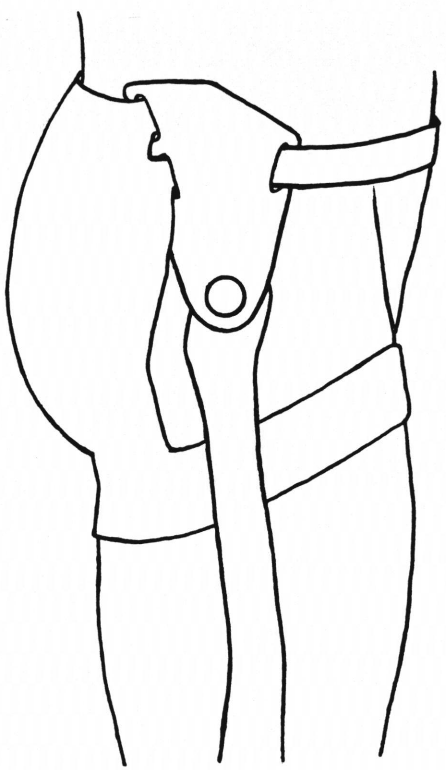
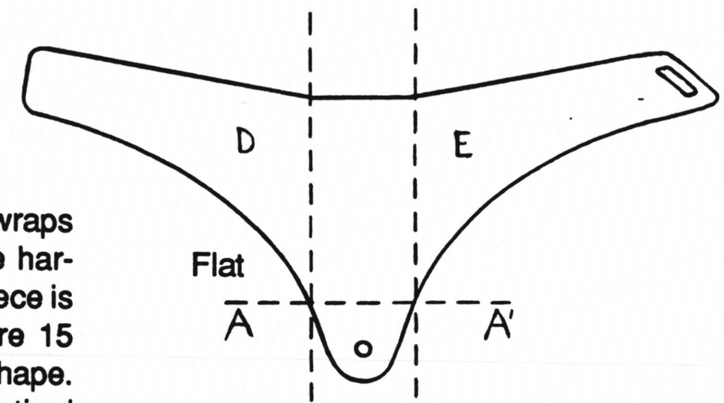


Figure 14. Original Harness Support

The new hip piece of the steel frame wraps partially around the waist to support the harness. The odd triangular shape of the piece is cut from a piece of sheet metal. Figure 15 shows the original shape and the formed shape. The triangular region provides a vertical component of support at the cantilevered section where the harness is suspended.

To compensate for the contour of the body, the top section is bent inward at a 15 degree angle around axis A - A'. Sections D and E are then rolled inward to follow the curve of the body, leaving the central region flat.

The slanted angle at the front of the hip piece helps to slip the harness loop into place. The angle is continued with the belt arrangement to avoid a single, out of place, slant. It is also used to balance the inward slope of the hip piece without the need to be symmetrical. Since the hip piece and buckle will be in different positions for different sized users, it is not possible to design a symmetrical arrangement. If a vertical orientation is used (as in Figure 16) it will only look appropriate if the vertical lines are symmetrical around the person's center line.



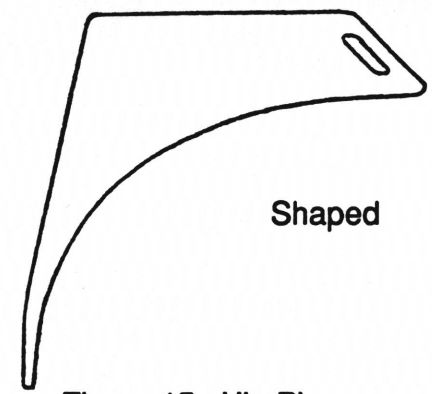


Figure 15. Hip Piece

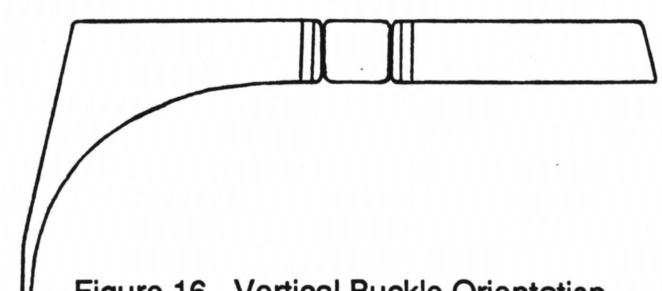


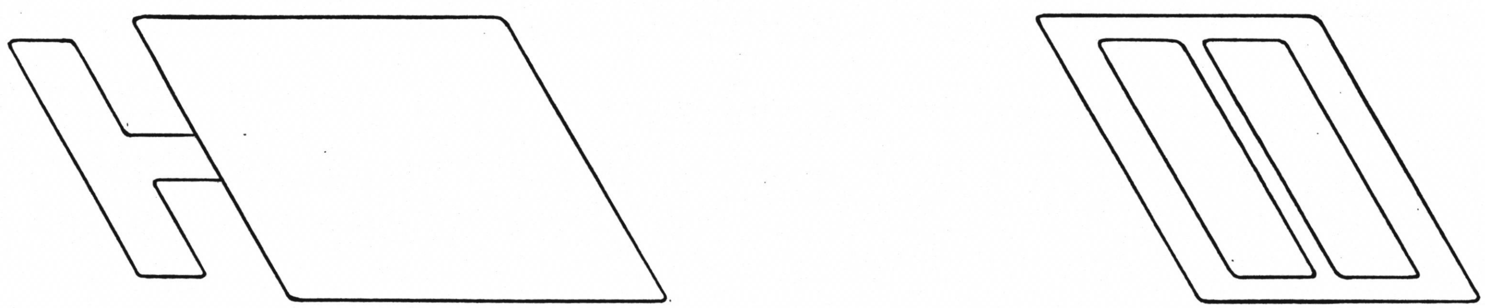
Figure 16. Vertical Buckle Orientation

After the harness is slipped onto the frame, the belt is fastened to secure the upper portion of the exoskeleton. The belt connection at the rear section of the hip piece can be riveted. It can remain permanently attached so it does not get separated from the crutch. Any pieces which separate completely would be at risk of getting lost or put in an unprotected place.

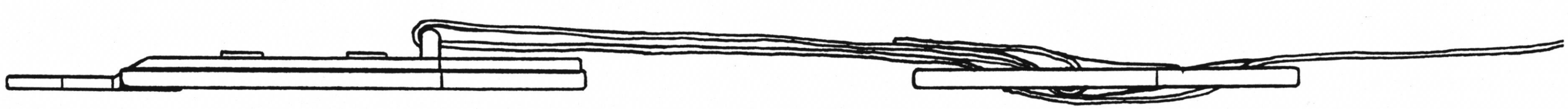
The belt connection at the front section of the hip piece needs to be easy to fasten and adjustable for different waist sizes. A hooking bar was chosen over other options to connect the belt and frame. It allows a simple attachment for the user which eliminates complicated mechanisms that can break. The slot in the frame piece does not interfere with the harness slipping into place. Other attachments required protruding pieces which make it difficult to put the harness on. A top view with the belt and front view of the connection without the belt is shown in Figure 17.

Different waist sizes can be adjusted by sliding the buckle along the belt. The end of the belt is secured to the center bar of the buckle while the hooking bar simply wraps the belt around a belt loop. As the buckle slides along the belt it lengthens or shortens the belt length.

Different materials are used for the belt surfaces. The outside shell is made of woven polyester strands for strength (similar to seatbelts in cars). The inside which is next to the user consists of a padded cotton surface. Vertical padded sections at two inch intervals allow air flow through the region for the user's comfort.



Front View



Top View

Figure 17. Belt Connection and Buckle

It is important for the loop of the harness to hang along the vertical axis where the ischium protrudes. Figure 18 shows the ischium position with respect to the outside hip region. This is the correct position to lift the body and maintain balance. Since different population sizes require a different distance x, the position where the harness hangs can be adjusted in two ways:

1)The cantilevered region rests at approximately a 3 degree angle pointing down toward the hip joint. This encourages the harness loop to slide to the outside as far as possible. Since the cantilever cross section increases in size toward the hip joint, the loop will stop at the last position it fits around. Therefore, the harness position can be adjusted by changing the size of the loop.

2)The inside curve of the hip piece must be secured against the user's hip in a comfortable manner. Foam cutouts can easily be velcroed onto the inside curve to cushion the frame. Foam pieces can be layered to a larger thickness to decrease the distance x for users requiring a smaller cantilever.

These measures may not be required for positioning in the final design. Once the testing frame harness is placed in the correct postition it does not move while walking or standing. The pull from the weight of the body maintains an adequate friction force between the harness and frame to avoid slipping. However, the two ways of positioning the harness may be used for finding the correct position each time the user puts on the crutch.

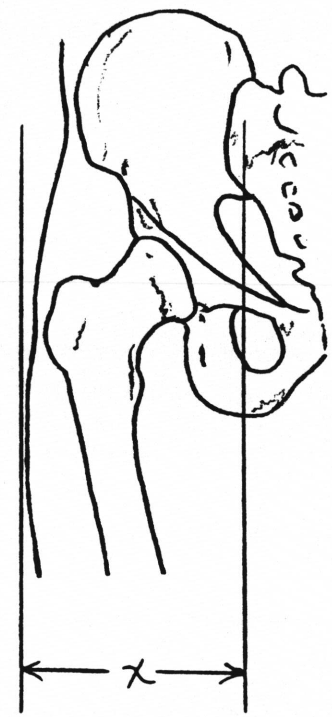


Figure 18. Ischium Lifting Position

Harness

The harness itself consists of two straps: one vertical strap which hooks onto the frame, and one leg loop which cradles the upper leg and pelvis to lift the impaired side. Shown here in Figure 19.

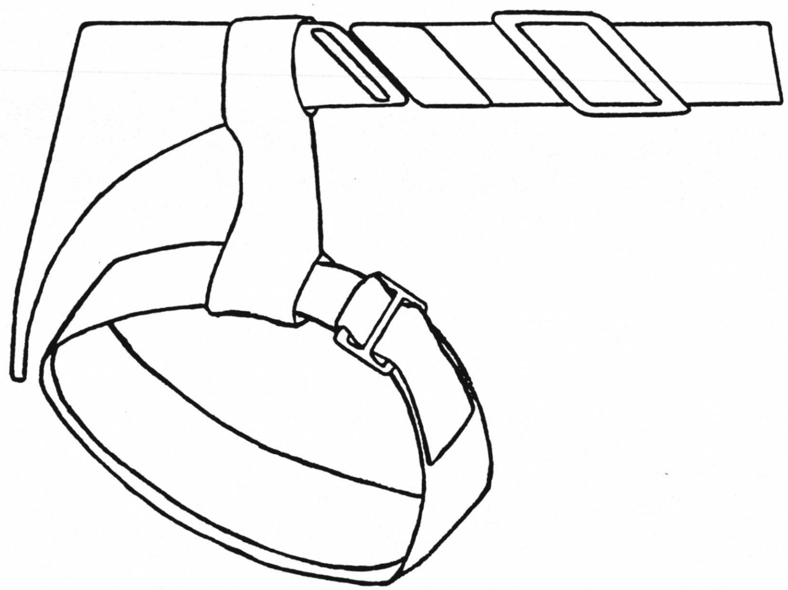


Figure 19. Adjustable Harness

The design has been modelled after rigging used for climbing. Like the belt, the leg loop is made with a cotton lined, intermittently padded inside, and a woven polyester outside shell. The vertical strap is made only from the polyester because it is not pressed against the user for extended time periods.

Different population sizes require that the leg loop be adjustable. It can also be the adjustment used for determining how much lift the crutch provides. The vertical strap is maintained at a relatively short length while the leg loop can be extended to the proper suspension height. A simple double back buckle will provide the stability and adjustability required. Those wearing the crutch over extended time periods can have the correct loop size sewn together to eliminate the buckle.

The strap for the harness provides a very small surface area to carry the entire weight of the body. This area is increased with an elliptical shaped thermoplastic support seat. A 1/8 inch piece of NCM spectrum thermoplastic measuring 7 inches long and 4 inches wide can multiply the area size under pressure by several times.

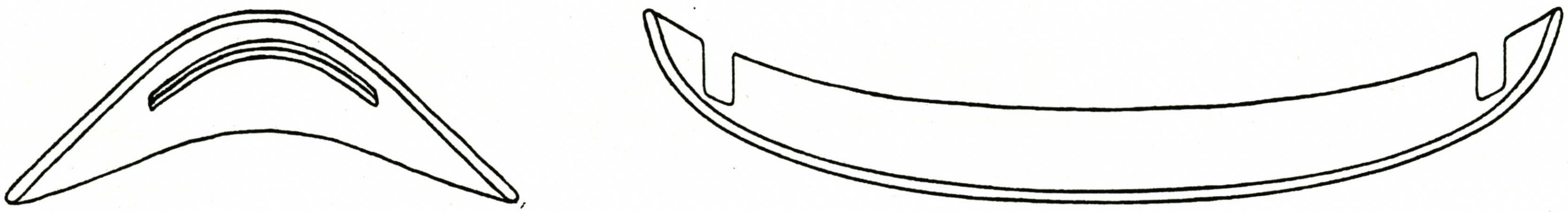
The thermoplastic sheet can be heated and cut into it's shape with holes for the harness. Then it can be molded to the crease where the buttock meets the leg. Figures 20a and 20b show the elliptical seat as designed and in the actual testing apparatus. Just like the other thermoplastic pieces, one general shape should fit a wide range of population sizes. This avoids the requirement of customized shaping for each user.

The two strap holes on the ends are threaded with the legloop which lifts from the underside of the seat.

A rectangular seat was originally used because it was easy to cut the shape out from a thermoplastic sheet. The lifting action of the harness applies a focused pressure at the corners of the rectangular seat. Without corners, the ellipse does not cut into the soft tissues as the seat lifts the body.

If longterm use is required, an additional hole can be cut into the ellipse where the ischial tuberosity protrudes. This small area has only a thin layer of protective tissue and is a common spot for pressure sores.

Figure 20b. Testing Apparatus Seat



End View

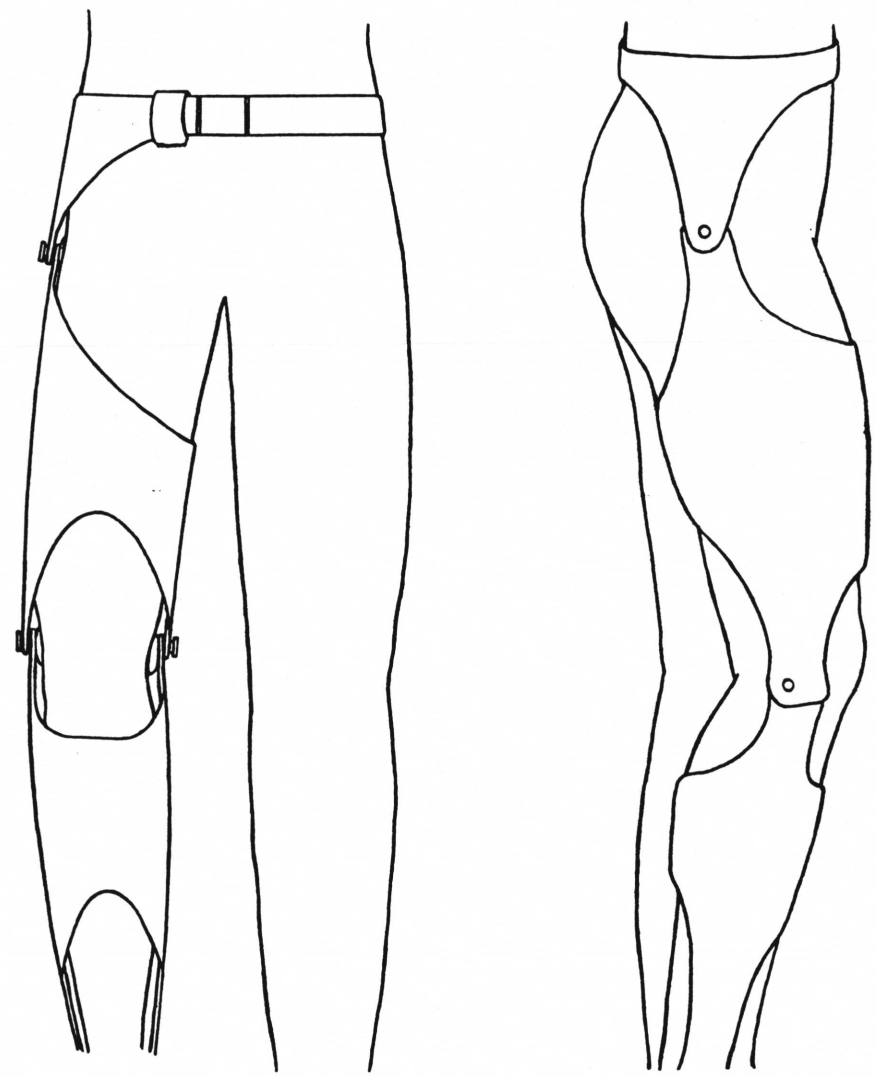
Side View

Figure 20a. Elliptical Plastic Seat

Joint Flexion

Suspending the impaired leg in the exoskeleton will add length to the disabled side. It's necessary for each leg to be equal in length in order to maintain a level sacrum. One option would be to raise the opposite leg an equal height. An insert could be placed in the user's shoe.

A second option is to lower the impaired leg height by flexing at the knee. Bending the knee and hip can compensate for the additional length while helping to provide the correct harness position. The lift provided by the harness encourages a slight angle between the body and the upper leg. This semi-sitting position keeps pressure off the sensitive tendons around the groin and places the force on the buttock area which is much better suited to carry the weight of the body. Since the angle of the thigh is forward relative to the vertical plane, the knee must remain at a slightly flexed position to maintain balance. Controlling the hip and knee angles can provide the proper crutch length for the individual user. Figure 21 shows the natural crutch as it would be worn in the slightly flexed position.



Front View   Side View

Figure 21. Slightly Flexed Position

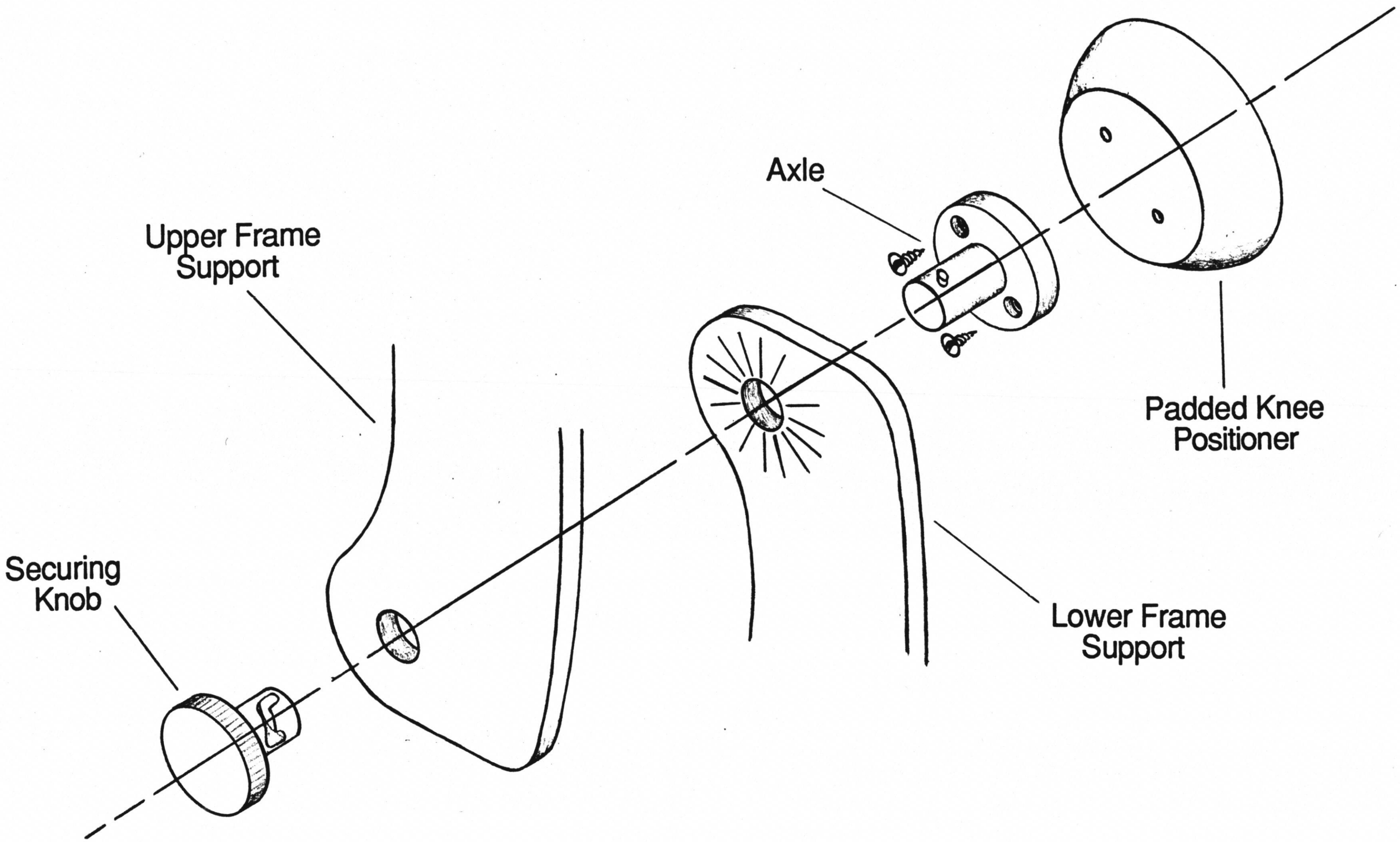


Figure 22. Joint Components

The crutch configuration requires strong knee and hip joints which can be easily adjusted to different angles. Figure 22 is an exploded view of the joint components. A circular air bladder is used to position and cushion the knee and hip next to the corresponding frame joints. The interlocking grooves around the holes on each of the frame pieces maintain the required angle once the joint is locked into place. The locking groove on the knob allows the user to easily unlock the hip joint in order to sit down. Both the knee and hip joints can make use of this adjustable arrangement.

The size of the grooves required to securely hold the knee at the correct angle does not provide a precise unit of adjustment. Since the overall length of the impaired side must be exact for a balanced sacrum, the height can be further adjusted by using the correct size rubber sole.

Two additional options have been conceived for control of the knee joint. Seen here in Figures 23 and 24. The first involves attaching one end of a lever to one of the frame supports. The other end of the lever is placed in a track where it's position can be controlled. There are adjustable limits on each end of the tapped track which can be positioned with and allen wrench. The supports rotate on two separate axes but they must rotate together. This way only one lever is required to control the angle of both supports.

The second option is much simpler and requires no extraneous moving parts. This concept encloses the joint on either side by adding plates parallel to the metal bars. Stops can then be screwed to the plates at the correct positions to control bending. Figure 24 shows two stops, one for flexion, one for extension.

These ideas are based on two points of rotation for the joint. Attempting to build a stabile frame with this configuration was extremely difficult. As a result, the design was simplified to the single point of rotation joint discussed on the previous page.

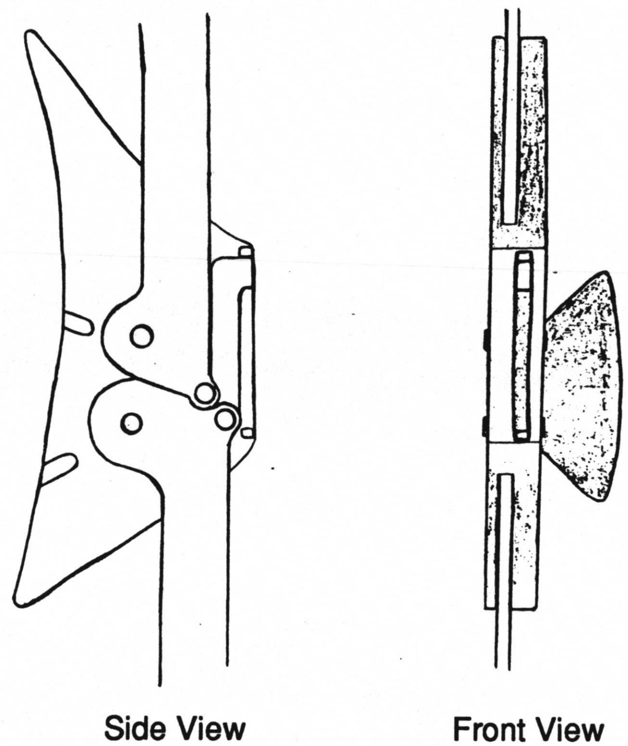


Figure 23. Lever Controlled Knee Joint

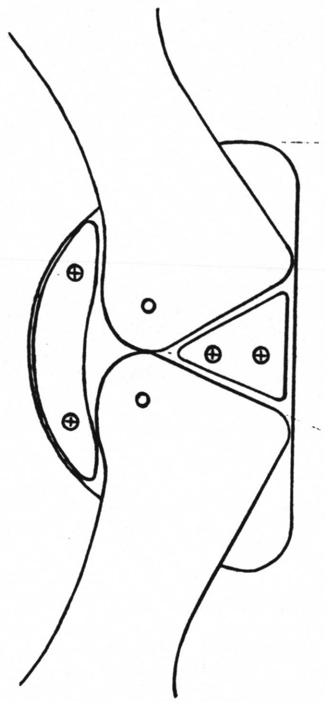


Figure 24. Stop Controlled Knee Joint

Crutch Height

If the crutch cannot be adjusted to the exact height required for a user (due to lack of needed parts, wearing, etc.), it should be adjusted too short as opposed to too tall. While wearing the testing frame at different heights two things were discovered. If the frame was too low compared to the unassisted leg it was awkward to use, but not uncomfortable. When the frame was too high, there was an immediate and sharp strain placed on the opposite hip joint. The body compensates much easier to a setting which is relatively lower than the other leg.

Setting the correct height involves combining the angle of knee flexion with the appropriate height rubber sole. This is a complicated relationship which involves the leg segment measurements of the individual being fitted. A spreadsheet has been set up to assist a fitter in determining the correct adjustments to make. Table 2 is an example of the spreadsheet output.

The fitter can input the estimated height for the rubber sole according to what is available and the user's foot size. The table then outputs the angle for knee flexion setting for different population sizes. If the crutch cannot be adjusted to the required angle, a new height can be put into the spreadsheet for another angle.

The X link corresponds to the length between the projected centers of rotation of the hip and knee joints. The Y link corresponds to the projected centers of rotation of the knee and ankle joints. The ranges on the table correspond to measurements from the 5th percentile female to the 95th percentile male in centimeters. All calculations used to determine this relationship are demonstrated in the appendix.

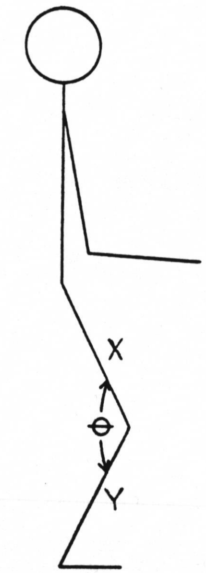


Table 2. Angle of Knee Flexion; Given Additional Height

INPUT ADDED SOLE HEIGHT IN cm 2.5 cm

THETA IS IN DEGREES

X LINK (cm)

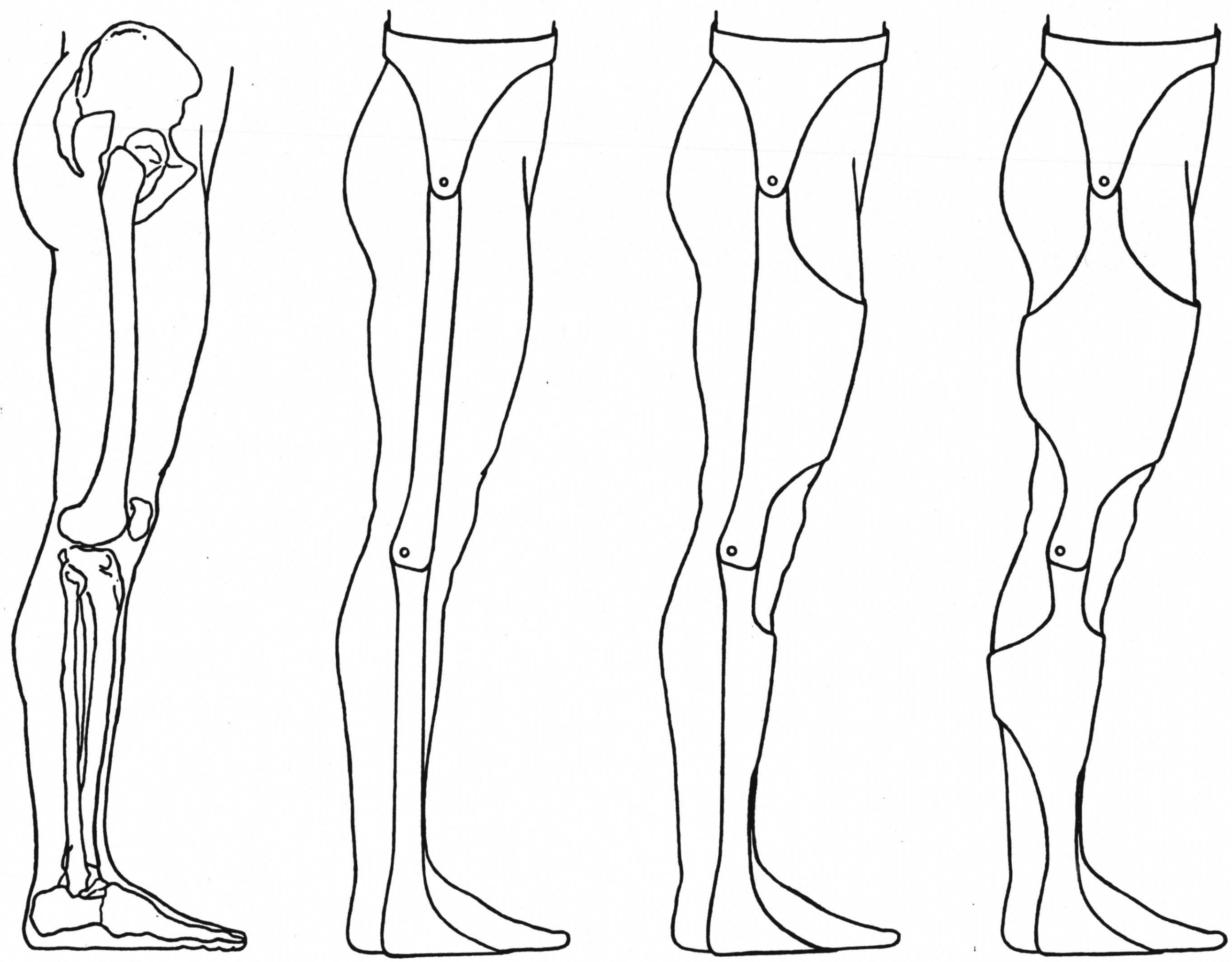
Y LINK (cm)

THETA	37	38	39	40	41	42	43	44	45	46
34	150	150	150	150	150	151	151	151	151	151
35	150	150	150	150	151	151	151	151	151	152
36	150	150	150	151	151	151	151	151	152	152
37	150	150	151	151	151	151	151	152	152	152
38	150	151	151	151	151	151	152	152	152	152
39	151	151	151	151	151	152	152	152	152	152
40	151	151	151	151	152	152	152	152	152	152
41	151	151	151	152	152	152	152	152	152	153
42	151	151	152	152	152	152	152	152	153	153
43	151	152	152	152	152	152	152	153	153	153
44	152	152	152	152	152	152	153	153	153	153
45	152	152	152	152	152	153	153	153	153	153
46	152	152	152	152	153	153	153	153	153	153

OVERALL CRUTCH

After incorporating ideas from the simulator testing into the design of the individual parts, the overall picture of the crutch changed in several ways. The progression of the exoskeleton is shown again in Figure 25 with the new changes in place.

Much of the similarity between the internal skeleton in 25a and the frame in 25b has disappeared. The hip piece is cantilevered to avoid loading the soft tissues on the inside of the thigh. It is more similar to a solid belt than an external representation of the pelvis.



a. b. c. d.

Figure 25. Revised Exoskelton Progression

Parts corresponding to the femur and tibia no longer match the natural curve. Sections through the middle of these vertical units were straightened to allow adjustability.

The support under the foot has been shortened and moved forward to the center of the foot. This reduces the bulk and properly aligns the foundation of the frame.

The knee joint has been changed into an overlapping single point of rotation. The actual knee is very complicated and already one of the most unstable parts of the body. For this reason, the frame joint is simplified to what can be mechanically stabilized.

In Figure 25d the plastic pieces are all in place on the attachment boxes. Because they cannot be connected all along the metal frame, these plastic pieces have been shortened for attachment to the shorter securing assembly length. The result is an exoskeleton which appears pieced together. The original concept is to appear as a unit with the leg; an extension of the leg's surface.

The concept is further disrupted when straps from the harness are added to the exoskeleton image. The harness can possibly be incorporated into a garment worn under the exoskeleton shell. If the straps were sewn into a pair of shorts, the crutch would display a more continuous appearance.

TESTING FRAME

A frame was built to test the concept of the natural crutch. One and a quarter inch steel bars were cut and shaped to the general design of the exoskeleton. Front and side views of the simulator are pictured here in Figure 26.

There are several differences between the frame used for testing and the actual design:

- The U-shaped base is threaded through the sole of a tennis shoe. It was built with the original intention of putting the exoskeleton inside the shoe but that was a difficult option to make work. Threading the sole also eliminates the need to build a shoe clamp or add a rubber sole underneath. The frame is threaded under the heel of the shoe not in the center. Walking with this support configuration produces a tendency to shift the foot back relative to the support.

- Anterior thermoplastic pieces have been replaced with curved metal bars bolted into place.

- Posterior plastic units are replaced with velcro straps to hold the leg in place.

- Both the knee and hip joints use a 5/16 inch diameter bolt for an axis and are locked into position with a second bolt.

- A solid hip piece was not available; several curved steel bars were shaped to the outline of the piece. The height of the piece relative to the body is also higher than the design.

Front View

Side View

Figure 26. Testing Frame

This was determined by the harness size available.

- A climbing harness has been disassembled and sewn back together according to the harness design. The only limiting factor is the vertical strap which is longer than the design; resulting in the need for a higher frame from which to hang the harness. The harness seat is cut from a thermoplastic sheet and formed according to design. These are pictured in Figure 27 on the following page. A simple belt attached to the harness is used to wrap around the hip piece and keep it in place.

- The frame sizes are not adjustable - it is custom built for one person to test. The only exceptions are the adjustable leg loop for the harness and height for the hip piece.

The outside thigh length for the testing frame used a much stronger steel bar than the other pieces. It required a 1 1/2 inch by 1/4 inch cross section hot rolled steel to avoid bending.

There is also a bending problem through the hip unit as weight is applied. This may be due to the insufficient simulation of the actual design. To compensate for the bending, a vertical support is attached from the quadricep region to the cantilevered section where the harness connects (Figure 28).

Figure 27. Testing Harness

This addition stabilized the frame and allowed ambulation without pressure applied to the leg in the crutch. The vertical addition may also be needed with the correct hip support in place. This idea deviates from the original concept, but could be integrated into the natural crutch design with some effort.

The testing frame was worn for various time intervals on numerous occasions over a period of two months. Without a disability, it was difficult to avoid naturally stepping with the leg in the exoskeleton. It required some training to relax the leg and allow the frame to support the weight. Once this was achieved is was quite easy to walk around indoors and outdoors and maneuver while wearing the crutch.

Sitting was almost impossible with the locked hip joint. This may partially be a result of the extra high hip piece; restricting more of the trunk than the lower height of the design. Without resolving this problem, a user would be in trouble should they fall while wearing the crutch.

Figure 28. Vertical Frame Support

Stairs were also maneuvered quite well without assistance from the railing. While descending stairs the crutch leg must precede the unassisted leg. During ascension, the unassisted leg must precede the crutch leg. Since each step must be taken in these orders, the process is slowed down compared to unassisted stair climbing.

The testing frame inroduced several problem areas which fail to meet the design objectives. These are summarized in the following section.

UNRESOLVED ISSUES

Many of the difficulties encountered with the crutch design have yet to be resolved. A summary of those aspects not meeting the objectives of the project are listed here.

Rigid Gait

Locking the joints in place eliminates the natural motions of the ankle, knee, and hip while walking. Of these, it is the locking of the hip joint which most radically affects the rigid gait. Figure 29 demonstrates how the trunk to upper leg angle moves through a wide range in an unassisted walking pattern. With the natural crutch, the leg must still move through it's motion while propelling the body forward. Since the joint does not move, the trunk of the body must follow the angle of the leg; forcing a rocking motion of the trunk through stride.

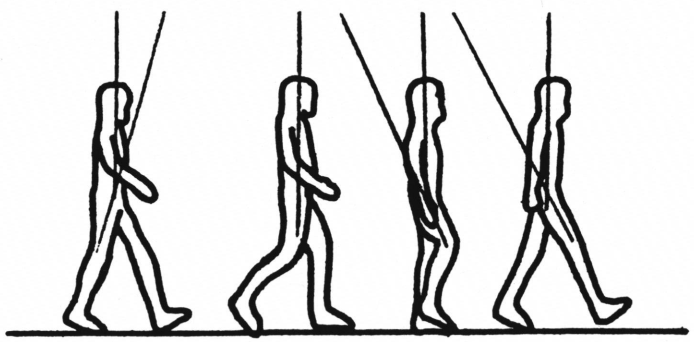


Figure 29. Trunk-Upper Leg Angle

Motion through the lower trunk is greatly decreased as the size of the steps taken is decreased. It can also be improved by lowering the height of the frame hip piece. Ideally, a structure which pushes up the seat could be used in place of the suspension hip section. The idea is similar to a seat which walks with the user at every step.

The knee and ankle joints could benefit by an arrangement which allows the joints to extend through stride and then lock at the correct flexion limit on impact. This would eliminate some rigidity in the crutch and provide exercise to the joints. Both additional options for the knee joint include a range of motion with each stride. The hip joint, however, must remain fixed to stabilize the harness. Designing in motion of this joint must consider the resulting motion of the trunk of the body.

NOTE: Any person using the natural crutch should be on a stringent physical therapy program to compensate for the lack of stimulation to the impaired limb.

Transfer

Transfer into and out of the crutch requires many steps and some training. The harness must first be pulled onto the leg and held in place by looping it onto the frame; at this point the hip joint is not secured so there is no tension on the harness. The hip piece is rotated forward as the user must lean over to secure the lower exoskeleton.

The foot can then be put into the shoe and secured. The shoe remains in the crutch at all times to avoid reassembling the clamping apparatus. The knee is then centered in the frame and the calf piece latched into place.

As the hip rests into the curved section the hamstring piece can be latched, securing the leg in place. The belt is hooked into the hip piece at the front while it is still rotated forward.

To move the hip member in place and lock the joint, the user must lean over on the supporting leg and push the crutch down the impaired leg (this eliminates tension from the harness). Once the hip piece is at the correct angle the knob on the joint can be turned to lock it in place. This must be repeated each time the user wishes to sit down and stand back up.

This sequence is too complicated and relies on the coordination of the user. Another option in the sequence above is to secure the entire frame before looping the harness into position. This requires a means to hold the harness up while putting on the exoskeleton; it tends to fall down the leg.

Seat Pressure

Testing found that even with the added thermoplastic seat there is too much concentrated pressure on the tendons below the ischium. Options in the future may include an elastic suspension unit, a larger cradle-type seat, and variations on padding and support. Different angles between the pelvis and thigh may also be tested to alleviate concentrated forces.

Instability

The body weight in the harness applies a downward force on the frame at the cantelevered section. The matching force travels up the exoskeleton a distance y from the harness connection. Figure 30 demonstrates how a moment is generated. This promotes a tendency for the frame to bend inward, while applying pressure to the inner thigh in the lateral direction. As the user steps with the crutch the body's center of gravity falls away from the crutch and downward.

A simple vertical support from the quadricep region of the frame up to the harness connection balances the forces in the exoskeleton. Though this deviates largely from the original concept, with some effort the support could be integrated into the natural crutch.

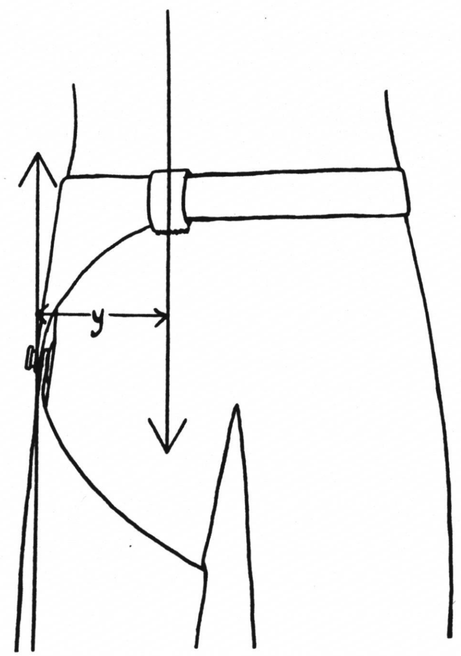


Figure 30. Moment Generated in Frame

Weight

The heaviness of the crutch aggravates the discontinuous gait and necessitates more energy output from the user. The large load the frame is required to carry makes it necessary to use a high strength material. Materials meeting the strength requirements tend to have high mass to volume ratios. After some consultation and research, the best steel found for the frame is a magnesium alloy stainless which has been precipitation hardened. Though aluminum alloys are much lighter, they do not exhibit the strength properties needed [19].

Investigation into different support orientations and available materials will develop a much lighter crutch. One particular area of promise is the field of high strength plastics.

Complicated Mechanisms

Each of the connections looks as though it was forced together. A good design should look like the pieces belong together in one continuous unit. Each member and connection could be a project in itself to find an optimal design. This proposal is a good starting position to now simplify and define a clear function for each of the sections of the crutch.

CONCLUSION

The concept of the natural crutch is to assist a lower leg impairment by following the natural biomechanical support structure of the body. This idea was developed from the design perspective: If an object is designed with a complete understanding of it's function, it will be formally exceptional. These concepts can be used to develop a product which will have a positive impact on the user's self-perception and avoid unnatural loading of the upper body.

The new crutch design will be able to help those who are unable to apply pressure to one of their legs. This may include user's with short term disabilities such as broken bones, severe strains, or surgical recuperation. It may also assist those with chronic conditions such as permanent injuries, minor deformities, or aggravated joints. Due to the lack of stimulation to the impaired limb while wearing the natural crutch, all users should enroll in a physical therapy program to counteract these affects. Though this should be a priority to help deal with the impairment, many disabled people do not make use of available rehabilitation resources.

Conventional crutch designs which have proved useful for a long time pose many problems to the user's interaction with their environment. A multifaceted design effort could alleviate several of these problem areas and improve the lives of many of the disabled. The optimum design situation includes perspectives from as many sides as possible. Input from the worlds of engineering, industrial design, marketing, manufacturing, even the user's perspective can help develop the best product possible.

A testing frame built to simulate the concept of the natural crutch found several areas where the objectives were not met: The stride of the crutch is a rigid motion requiring the body to rotate the impaired leg forward. The seat of the harness applies too much concentrated pressure to the tendons above the hamstring. There is also a tendency for the crutch to bend toward the user causing some instability (this may have been due to an insufficient simulation of the hip piece). Transfer in and out of the crutch is tricky and requires some training. Finally, the frame needed to carry the user's body weight is quite heavy and difficult to carry around.

The proposal submitted in this paper should be considered a starting point from which a design can be refined to where it can be mass produced for the temporarily and permanently disabled communities. From this point, projects can be set up to investigate resolutions for the problems described above. This includes the possibility of incorporating a vertical support at the thigh region. Once the problem areas are redesigned, dimensions can be specified for the individual components. This information can then be used to assemble a working prototype of the natural crutch design.

A prototype developed according to the design specifications can be used to scientifically test compliance with the original objectives. It is possible to measure where the load travels (through the crutch or the leg) in force analysis trials. It wil also be possible to measure improvements in gait by videotape analysis.

Refinements of the design following prototype testing can be integrated and retested until a safe and useful prototype is assembled. Manufacturing procedures can then be developed for mass production. Based on current prices for assistive devices, a projected cost for the crutch is $500 - $800 retail [11]. In order to include a temporary market, distribution strategies should incorporate options for a leasing program. This is one reason for the adjustability design requirement (each user would require a professional fitter to make the correct size adjustments).

Continuation of the natural crutch project should eventually provide an assistance product which will help many people in the future.

APPENDIX - CALCULATIONS

1. Adjusted Crutch Height
2. Joint Failure

    Direct Shear

    Moment Load Shear

    Bending of Axle

    Compression of Members (Bearing Load)

3. Lower Leg Support Failure

    Direct Load Buckling

4. Upper Leg Support Failure

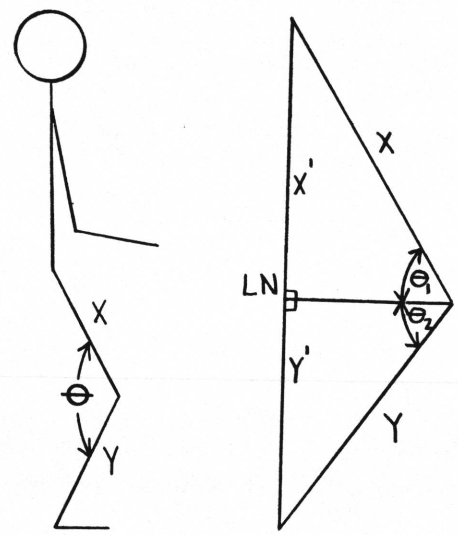
    Direct Load Buckling

5. Cantilever of Hip Piece Failure

    Bending

1. Adjusted Crutch Height

PURPOSE: To determine the angle of knee flexion required to maintain the correct crutch height given a particular added length (height of the rubber sole). If the knee joint is unable to secure at the required angle, a new sole should be used and a different angle calculated.



A spreadsheet has been set up to help calculate the different angles for a wide range of sizes. Table 3 below is an example of the output. A fitter inputs the height of the sole to be used and the table calculates the angle required at knee flexion. It is a different sample than presented in the main text. The ranges of sizes indicate the 5th percentile female through the 95th percentile male in centimeters for both leg measures.

GIVEN: Length of thigh X
Length of shank Y
Height of rubber sole H

Note: X and Y should be measured as the length between projected centers of rotation for the ankle, knee, and hip joints.

PROCEDURE:

1. Find Leg Length L = X + Y

2. Find Needed Length LN = L - H

3. Find X' = (X) (LN) / L and

   Y' = (Y) (LN) / L

4. Find

   THETA 1 = INV SIN ((X') (SIN 90) / X)

   and

   THETA 2 = INV SIN ((Y') (SIN 90) / Y)

5. Find THETA = THETA 1 + THETA 2

Table 3. Angle of Knee Flexion; Given Additional Height.

INPUT ADDED SOLE HEIGHT IN cm 3.5 cm

THETA IS IN DEGREES

X LINK (cm)

Y LINK (cm)

THETA	37	38	39	40	41	42	43	44	45	46
34	144	144	144	145	145	145	145	146	146	146
35	144	144	145	145	145	145	146	146	146	146
36	144	145	145	145	145	146	146	146	146	146
37	145	145	145	145	146	146	146	146	146	147
38	145	145	145	146	146	146	146	146	147	147
39	145	145	146	146	146	146	146	147	147	147
40	145	146	146	146	146	146	147	147	147	147
41	146	146	146	146	146	147	147	147	147	147
42	146	146	146	146	147	147	147	147	147	148
43	146	146	146	147	147	147	147	147	148	148
44	146	146	147	147	147	147	147	148	148	148
45	146	147	147	147	147	147	148	148	148	148
46	147	147	147	147	147	148	148	148	148	148

The following calculations determine the stresses through different frame components and some options for component dimensions. Failure due to these stresses will be determined by the designers choice of materials, component dimensions, and factors of safety considered. Stress concentration factors, combined stresses, and fatigue effects have not been entered into analysis. These calculations can be performed once the design of components is refined and dimensions have been determined. A high factor of safety and prototype testing can also compensate for lack of elaborate force analysis.

<u>2. Joint Failure - Direct Shear</u>

PURPOSE: To determine the direct shear load placed on the joint.

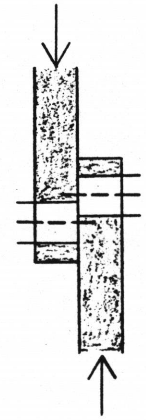
GIVEN: F = Maximum Load
A = Cross Sectional Area of Axle
r = Axle Radius

ASSUME: All of the shear load is taken by the axle. Some is also supported by the interlocking grooves around the joint, but force distribution is too complicated to determine. The entire load is passed through one joint.

PROCEDURE:

Shear Stress = F/A

A = (PI) (r)^2



A spreadsheet has been set up to determine the direct shear stress on the axle for different diameters. Table 4 shows the range of stresses for different axle diameters and different maximum loads. The force range represents the 5th percentile female body weight to the 95th percentile male body weight.

Table 4. Shear Stress in the Joint Axle

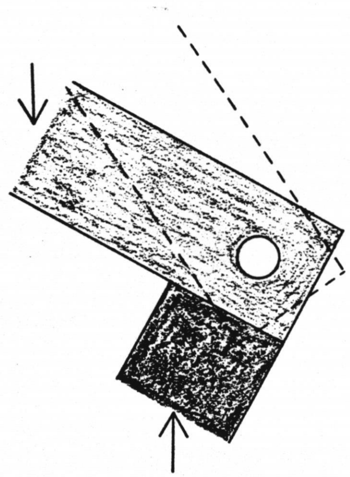
Diameter (cm)

	Stress	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
	461	147	36.7	16.3	9.18	5.87	4.08	3	2.29	1.81	1.47
	561	179	44.7	19.9	11.2	7.15	4.96	3.65	2.79	2.21	1.79
F (N)	661	211	52.6	23.4	13.2	8.42	5.85	4.3	3.29	2.6	2.11
	761	242	60.6	26.9	15.1	9.69	6.73	4.95	3.79	2.99	2.42
	861	274	68.6	30.5	17.1	11	7.62	5.6	4.28	3.39	2.74
	961	306	76.5	34	19.1	12.2	8.5	6.25	4.78	3.78	3.06

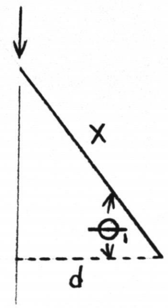
Stress is in MPa

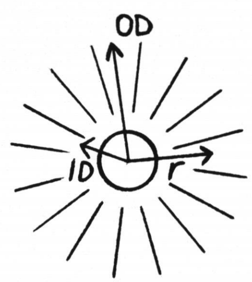
2. Joint Failure - Moment Load Shear

PURPOSE: The determine the shear load placed on the interlocking grooves around the knee joint.This shear is produced by the off center load attempting to bend the knee joint.



GIVEN: F = Maximum Load
- X = Length of Upper Leg Section
- Theta 1 = Angle Between the Horizontal and the Upper Leg Section
- d = Distance Between the Applied Load and the Center of the Joint Along the Horizontal Axis
- ML = Moment Load
- A = Projected Surface Area of the Grooves
- ID = Inner Diameter of the Groove Area
- OD = Outer Diameter of the Groove Area
- r = Distance From the Center of the Joint to the Point Halfway Between the ID and OD





ASSUME: The active load passes through a single joint. Uniform distribution of forces over the projected contact area. The moment load is taken completely by the grooves; though any preload on the joint will assist with friction.

PROCEDURE:

Shear = ML / A

A = (Pi) (OD / 2)^2 - (Pi) (ID / 2)^2

ML = (F) (d) (r) / (r)^2 = (F) (d) / (r)

d = (X) (cos(Theta 1))

Set conservative estimates for maximum load and groove dimensions:

Let F = 960 N, ID = 1.5 cm, OD = 3.0 cm:

A = 5.3 cm squared; r = 2.25 cm

ML = (960 N) (d) / (2.25 cm/100)

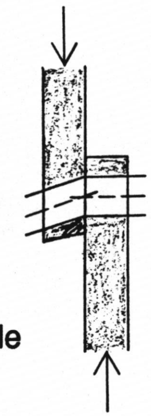
A spreadsheet has been set up to help determine the moment load shear for different values of X and Theta 1. Table 5 below shows the output in megapascals.

Table 5. Moment Load Shear

		X LINK (cm)							
	Stress	38	39	40	41	42	43	44	45
THETA 1 (Degrees)	65	12.6	12.94	13.28	13.63	13.97	14.31	14.65	14.99
	68	11.17	11.48	11.78	12.08	12.38	12.68	12.99	13.29
	71	9.715	9.978	10.24	10.5	10.77	11.03	11.29	11.55
	74	8.229	8.451	8.674	8.896	9.119	9.341	9.563	9.786
	77	6.72	6.902	7.083	7.265	7.447	7.628	7.81	7.992
	80	5.193	5.333	5.474	5.614	5.754	5.895	6.035	6.176

Stress in MPa

2. Joint Failure - Bending of Axle



PURPOSE: To determine the bending stresses which would cause the axle to deform at failure.

GIVEN: F = Maximum Load
t = diameter of axle = d
I = Moment of Inertia for a Circle
c = ymax

ASSUME: The entire load passes through a single joint. The load is distributed evenly.

PROCEDURE:

Bending Stress = (M) (c) / (i)

M = (F) (t) / 2

I = (Pi) (d)^4 / 64

c = d / 2

Redefine in terms of diameter:

Bending Stress = (5.09) (F) / d^2

A spreadsheet has been set up to determine the bending stress as a result of different axle diameters and maximum loads. Table 6 shows the output in megapascals (MPa) for a range of body weights (5th % Female - 95th % Male).

Note: Failure due to bending of the members about the joint is difficult to accurately determine. This is because of the intricate distribution of the load throughout the region. Shigley and Mitchell put it "It is seldom used in design; instead it's effect is compensated for by an increase in the factor of safety."

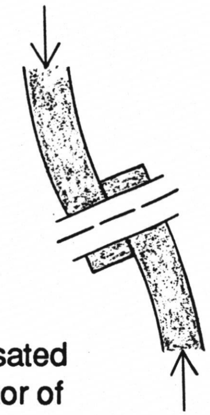


Table 6. Bending Stress in the Joint Axle

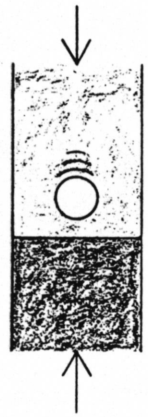
Diameter (cm)

F (N)

Stress	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
461	587	147	65.2	36.7	23.5	16.3	12	9.17	7.24	5.87
561	714	178	79.3	44.6	28.6	19.8	14.6	11.2	8.81	7.14
661	841	210	93.5	52.6	33.6	23.4	17.2	13.1	10.4	8.41
761	968	242	108	60.5	38.7	26.9	19.8	15.1	12	9.68
861	1096	274	122	68.5	43.8	30.4	22.4	17.1	13.5	11
961	1223	306	136	76.4	48.9	34	25	19.1	15.1	12.2

Stress is in MPa

2. Joint Failure - Compression of Members



PURPOSE: The determine the bearing stresses which would result in deformation of a member due to a bearing load.

GIVEN: F = Maximum Load
t = Thickness of Member
d = Diameter of Axle
A = Projected Contact Area Between the Axle and Member

ASSUME: The active load passes through a single joint. Uniform distribution of forces over the projected contact area.

PROCEDURE:

Bearing Stress = F/A

A = (t) (d)

Set the maximum load = 960 N:

Bearing Stress = 960 N/[(t) (d)]

A spreadsheet has been set up to determine the bearing stress as a result of different axle diameters and member thicknesses. Table 7 shows the output in MPa for a maximum load of 960 N.

Table 7. Bearing Stress in the Joint Member

Diameter (cm)

Thickness (cm)	Stress	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
	0.1	480	240	160	120	96	80	68.6	60	53.3	48
	0.3	160	80	53.3	40	32	26.7	22.9	20	17.8	16
	0.5	96	48	32	24	19.2	16	13.7	12	10.7	9.6
	0.7	68.6	34.3	22.9	17.1	13.7	11.4	9.8	8.57	7.62	6.86
	0.9	53.3	26.7	17.8	13.3	10.7	8.89	7.62	6.67	5.93	5.33
	0.11	436	218	145	109	87.3	72.7	62.3	54.5	48.5	43.6
	0.13	369	185	123	92.3	73.8	61.5	52.7	46.2	41	36.9
	0.15	320	160	107	80	64	53.3	45.7	40	35.6	32

Stress is in MPa

3. Lower Leg Support Failure - Buckling

PURPOSE: To determine the necessary member dimensions to support a range of maximum loads which result in buckling. These dimensions reflect the smallest cross section of the support - it's weakest point.

GIVEN: Pcr = Critical Load
E = Material Modulus of Elasticity
I = Moment of Inertia for a Rectanglar section
L = Length of Column
w = width of cross section
t = thickness of cross section

ASSUME: Lower leg support acts as a Euler column with two fixed ends that buckles at it's critical load (Pcr). The entire load passes through a single support. Rectangular cross section.

PROCEDURE:

Pcr = (4) (Pi)^2 (E) (I) / L^2

Solve for I:

I = (Pcr) (L)^2 / [(E) (4) (Pi)^2]

An interactive program has been set up on a spread sheet to assist with these calculations and supply dimension options. Output from the program is mixed into the procedure.

Choose a material and enter it's Modulus of Elasticity in the program. Table 8 shows the output of moment of inertia ranges for the ranges of column lengths and critical loads given.

Table 8. Lower Leg Support Moment of Inertia

Input Modulus of Elasticity 127 GPa

Length (cm)

Pcr (N) \ I	10	15	20	25	30	35	40
461	9.2E-05	0.00021	0.00037	0.00058	0.00083	0.00113	0.00147
561	0.00011	0.00025	0.00045	0.0007	0.00101	0.00137	0.00179
661	0.00013	0.0003	0.00053	0.00082	0.00119	0.00162	0.00211
761	0.00015	0.00034	0.00061	0.00095	0.00137	0.00186	0.00243
861	0.00017	0.00039	0.00069	0.00107	0.00155	0.00211	0.00275
961	0.00019	0.00043	0.00077	0.0012	0.00173	0.00235	0.00307

I is in cm^4

From Table 8 determine which moment of Inertia applies and enter it into the program. Table 9 then generates the appropriate widths for a range of member thicknesses based on

I = (w) (t)^3 / 12

for a rectangular cross section.

Table 9. Support Member Dimensions

Input Moment of Inertia 0.00113 cm ^4

t	w
0.2	1.695
0.4	0.212
0.6	0.063
0.8	0.026
1	0.014

All units in cm

4. Upper Leg Support Failure - Buckling

PURPOSE: To determine the necessary member dimensions to support a range of maximum loads which result in buckling. These dimensions reflect the smallest cross section of the support - it's weakest point.

GIVEN: Pcr = Critical Load
E = Material Modulus of Elasticity
I = Moment of Inertia for a Rectanglar section
L = Length of Column
w = width of cross section
t = thickness of cross section

ASSUME: Upper leg support acts as a Euler column with one fixed end and one free end that buckles at it's critical load (Pcr). The entire load passes through a single support. Rectangular cross section.

PROCEDURE:

Pcr = (Pi)^2 (E) (I) / [(4) (L)^2]

Solve for I:

I = (4) (Pcr) (L)^2 / [(E) (Pi)^2]

An interactive program has been set up on a spread sheet to assist with these calculations and supply dimension options. Output from the program is mixed into the procedure.

Choose a material and enter it's Modulus of Elasticity in the program. Table 10 shows the output of moment of inertia ranges for the ranges of column lengths and critical loads given.

Table 10. Upper Leg Support Moment of Inertia

Input Modulus of Elasticity 127 GPa

Length (cm)

Pcr (N)	I	10	15	20	25	30	35	40
	461	0.00147	0.00331	0.00589	0.0092	0.01325	0.01804	0.02356
	561	0.00179	0.00403	0.00717	0.0112	0.01613	0.02195	0.02867
	661	0.00211	0.00475	0.00845	0.0132	0.019	0.02587	0.03378
	761	0.00243	0.00547	0.00972	0.01519	0.02188	0.02978	0.0389
	861	0.00275	0.00619	0.011	0.01719	0.02475	0.03369	0.04401
	961	0.00307	0.00691	0.01228	0.01919	0.02763	0.03761	0.04912

I is in cm^4

From Table 11 determine which moment of Inertia applies and enter it into the program. Table 9 then generates the appropriate widths for a range of member thicknesses based on

I = (w) (t)^3 / 12

for a rectangular cross section.

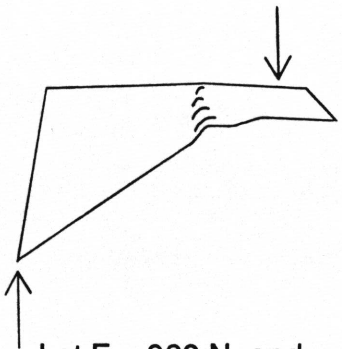
Table 11. Support Member Dimensions

Input Moment of Inertia 0.01519 cm ^4

t	w
0.2	22.79
0.4	2.848
0.6	0.844
0.8	0.356
1	0.182

All units in cm

5. Cantilever of Hip Piece Failure - Bending



PURPOSE: To determine the bending stresses which would cause the hip piece to deform at failure.

GIVEN: F = Maximum Load
t = Thickness of Cross Section
w = Width of Cross Section
I = Moment of Inertia for a Rectangle
c = ymax
x = Distance from Deformation to the Applied Downward Load

ASSUME: The piece acts as a simple rectangular cross section cantilever. The piece will fail about the shortest axis (just as the testing frame deformed).

PROCEDURE:

Bending Stress = (M) (c) / (I)

M = (F) (x)

I = (w) (t)^3 / 12

c = t / 2

Redefine in terms of thickness t:

Bending Stress = (12) (F) (x) / [(w) (t)^2)]

A spreadsheet has been set up to determine the bending stress as a result of different cross sections. For a conservative estimate, the maximum load and distance x will be used to calculate the stress.

Let F = 960 N, and x = 25 cm (conservative estmate of the maximum distance):

Bending Stress =

(12) (960 N) (25 / 100) / [(w) (t)^2)]

Bending Stress = 2880 / [(w) (t)^2)] in Pa

Table 12. Bending Stress in the Hip Piece

Thickness (cm)

Width (cm)

Stress	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8
1	0.07	0.02	0.01	0	0	0	0	0	0
2	0.04	0.01	0	0	0	0	0	0	0
3	0.02	0.01	0	0	0	0	0	0	0
4	0.02	0	0	0	0	0	0	0	0
5	0.01	0	0	0	0	0	0	0	0
6	0.01	0	0	0	0	0	0	0	0

Stress is in MPa

Since this result is negligible, it is assumed that the failure in the testing frame is the result of poor simulation of the design.

REFERENCES

1. American Orthotics and Prosthetics Assoc.: Orthotics and Prosthetics Vol. 32. U. S., 1978.

2. Epstein, S.: "Art History and the Crutch." Ann Med Hist 9:304-313, 1937.

3. Patterson, R., Fisher, S. V.: "Cardiovascular Stress of Crutch Walking." Arch Phys Med Rehabil 62:257-260, 1981.

4. Wells, R. P.: "The Kinematics and Energy Variations of Swing-Through Crutch Gait." J Biomech 12:579-585, 1979.

5. Shoup, T. E., Fletcher, L. S., Merrill, B. R.: "Biomechanics of Crutch Locomotion." J Biomech 7:11-19, 1974.

6. Childs, T. F.: "An Analysis fo the Swing-Through Crutch Gait." Physical Therapy 44(9):804-807, 1964.

7. Fuller, David, D. O.: Chicago School of Osteopathic Medicine, Chicago, Ill.

8. Opila, K. A., Nicol, A. C., Paul, J. P.: "Upper Limb Loadings of Gait with Crutches." J Biomech Eng Nov;109(4):285-90, 1987.

9. Shabas, D., Scheiber, M.: "Suprascapular Neuropathy Related to the Use of Crutches." Am J Phys Med Dec;65(6):298-300, 1986.

10. Malkan, D. H.: "Bilateral Ulnar Neuropraxia: a Complication of Elbow Crutches." Injury 23(6):426, 1992.

11. St. Louis Medical Supply Catalog, St. Louis, 1992.

12. Showers, Joseph: The Potential for Commonality in Architectural and Engineering Design. Virginia Polytechnic Institute and State University, 1982.

13. Hobson, D. A.: "Seating and Mobility for the Severly Disabled." Rehabilitation Engineering, CRC Press, Boston, 1990.

14. Rehab Group Inc.: Digest of Data on Persons With Disabilities. U. S. Government Printing Office, Washington D. C., 1980.

15. Mitchell, L. P.: Data on Disability From the National Health Interview Survey, 1983-1985. An Info Use Report. Washington D. C.: U. S. National Institute on Disability and Rehabilitation Research.

16. North Coast Medical, Inc.: Hand Therapy Catalog. San Jose, CA, 1992.

17. Shigley, J. E., Mitchell, L. D.: Mechanical Engineering Design. McGraw-Hill, 1983.

18. Lam, P., Reddy, N., and Downing, M.: "One More Step in Redesigning the Ankle-Foot Orthotic." SOMA: Engineering for the Human Body, 2(1):36-39, 1987.

19. Shackelford, J. F.: Introduction to Materials Science for Engineers. Macmillan, New York, 1985.

20. Chaffin, D. B., Anderson, G.: Occupational Biomechanics. Wiley & Sons, 1991.

ABSTRACT

The proposed "natural crutch" provides ambulation assistance without the problems associated with arm-supported crutches. The new crutch has an exoskeleton structure which surrounds the disabled leg and carries the user's body weight while walking and standing. The load is transferred from the exoskeleton to the trunk of the body through a harness which lifts the pelvis on the impaired side. The intention is to simulate the internal skeleton's natural load distribution while compensating for the impairment.

The crutch design is presented as a unique concept with an outlined proposal for a marketable prototype. Results of a full scale simulator test are used to determine areas requiring further development. All aspects of design attempt to include both engineering and industrial design perspectives.