FURTHER STUDY OF THE FEASIBILITY OF A WHEELED ABOVE-KNEE PROSTHESIS AND DESIGN OF A LIGHTWEIGHT PROTOTYPE

By

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SUBMITTED IN PARTIAL FULFILLMENT
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May 6,1988

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Submitted to the Department of Mechanical Engineering
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Abstract

A prototype of a wheeled above-knee prosthesis intended for non-amputee test subjects was built and evaluated. It was designed to be both lightweight and maneuverable on various surfaces and at different speeds. Most of the design effort focused on minimizing the weight of the prototype.

A previous prototype had been constructed of aluminum. Wood was chosen for the new design because of its high stiffness-to-weight ratio. This new design used laminated mahogany curved to form a crutchlike 'socket'. The shank and foot-like frame for the wheels were constructed of oak. The prototype was not as stiff as the original, and therefore produced marginal controllability. Also, when a peak load was simulated, the wood failed at the ankle joint. In future designs, both stiffness and strength clearly must be increased. Recommendations for future lightweight protoypes and for rolling prosthesis research in general were made.

Thesis Supervisor: Woodie C. Flowers

Title: Professor of Mechanical Engineering

To mumma and dad
and the rest of my family and friends
whom I love so much.

Acknowledgments

I would like to acknowledge everyone who helped make this project possible.

First and foremost is Prof. Woodie C. Flowers. His gentle pushes and encouragement, especially during the final stages of the project,were exemplary and made everything more interesting.

Next are Michael Kohlbrenner and Janet Zahradnik for laying the groundwork down for me. The work that they did provided a solid platform for me to operate on.

Jack Kotovsky is a friend of mine who deserves thanks. He attended many of the meetings with Woodie and provided us all with his special insight. He was also a brave enough soul to be a test subject. Hooray Jack!

I am not a fine crafstman. Fortunately for me Tiny Calogerro, Robert Samuel , and George Pishenin from the M.I.T. Hobby shop are, or my prototype would have performed more miserably than it did.

Allison Hochstein, Tom Stewart, Tim Sulzbach, and Stephanie Squarcia all volunteered to test a device that broke before they had a chance to. Their enthusiasm is appreciated.

Finally, I wish to dearly thank Teresa Zimmers, whose kindness and proof-reading skills pulled me through by the skin of my teeth.

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1. Introduction

For a person who loses the lower part of a leg (an above-knee, or a/k amputee), walking is usually one of the most important functions to regain. For this reason, a large amount of research has been put into prosthetic devices that simulate walking. The dynamics of walking are complex, however, and technology has not been able to produce an adequate alternate means of locomotion. Present prosthesis require twice as much energy as normal walking. Also, they are not as maneuverable as human limbs, as they lack control, flexibility, and degrees of freedom. Other solutions, such as wheelchairs and crutches, are not only less esthetically pleasing as some conventional prostheses, but also share similar control problems.

An ideal solution would be to create a 'leg' which simulates walking, but which requires less energy and provides greater mobility than present prostheses. An innovative design is a prosthesis with wheels. Rolling is efficient and provides increased mobility, as any skateboarder or bicyclist will verify. Wheels on a prosthesis, however, would create problems for an amputee that a skateboarder does not have to contend with. In skateboarding, the knees and ankles bend for balance and control. A wheeled prosthesis would not be flexible in the simulated knee and ankle joints. This approach has sufficient potential benefits to an amputee to warrant further study.

In 1985, Michael J. Kohlbrenner performed a study of the feasability of a wheeled prosthetic device. He used a skateboard wheel configurationin which steering was accomplished by leaning. The skateboard wheels were controllable and safe, and provided a reasonable amount of mobility at low energy cost. He reported positive results and suggested further study.

In 1987, Janet Zahradnik followed up with a study aimed at optimizing the wheel configuration. She compared the skateboard wheel configuration with a tandem wheel configuration similar to roller blades. Roller blades are highly maneuverable and can be controlled by a pivoting action. One of the goals of her study was to develop insight into the dynamics of controlling the rolling prosthesis. The results of this study, however, were somewhat inconclusive as to which wheel geometry was better. Some subjects preferred the skateboard wheel configuration, others the tandem wheels. The skateboard configuration seemed more stable. If the subject learned to balance the prosthesis with the roller blades, however, greater maneuverability was achieved.

The goal of this study is to design a lighter, more stable prosthesis than Kohlbrenner's. Skateboard wheels were chosen for the prototype. Although they were slightly less maneuverable, they provided a more stable platform to roll on. Initial studies confirmed that skateboard wheels with a wider wheelbase than Kohlbrenner's increased stability significantly. Thus, the wider wheelbase was implemented in the design. Wood was the material chosen for its favorable stiffness-to-weight ratio. The combined lighter weight and greater strength of wood provides improved controlability.

The long range purpose of this study is to build a more maneuverable prosthesis. Improved mobility of this prototype will help researchers further explore the limitations of any rolling prosthesis. This will aid in creating an optimal design, which should indicate the feasability of a wheeled prosthetic device.

2. Key Issues

The major issues which need to be adressed are safety, mobility, and cosmetics.

2.1 Safety

Safety is paramount in our design. There are obvious concerns with this particular prototype. Rolling provides decreased lateral mobility and stability. The device is not firmly planted. Also, unlike walking, rolling becomes more dangerous at higher speeds, and the wheels more senstive to small objects in their path. Though speeds for this wheeled prototype will be relatively low, as higher performance rolling prostheses are demanded, greater speeds will become an issue.

Another safety concern is control. Steering is essential to keep the amputee from hitting objects or people. Balance must be retained for the amputee's safety. Though skateboards and the rolling prosthesis are similarly controlled, i.e. by leaning in the direction of the turn, steering and balance are complicated in this prototype. With a skateboard, the knee and ankle can be flexed to execute a turn, whereas with a wheeled prosthesis the 'knee' and 'ankle' are rigid, making steering and balancing more difficult. Additionally, if the device is unstable or difficult to steer, the extra effort required to control it may cause discomfort or fatigue to the wearer which could make operation unsafe.

2.2 Mobility

Theoretically, a wheeled prosthesis provides greater mobility of an amputee than a regular prosthesis. Mobility is defined as the ability to negotiate a given terrain. The high mobility of rolling locomotion can be seen in skateboarding, roller-skating, and bicycling. These methods demonstrate the improved speed, energy conservation, and distance travelled of rolling locomotion. Other mobility issues which a wheeled prosthesis must resolve acceptably are controllability, freedom, and the ability to travel on different terrains.

Rolling improves speed and energy conservation because there is no change in the center-of-gravity, and therefore no work is wasted in the vertical directions. Additionally, wheels are very efficient. Energy is stored in momentum during the coasting period of each stride. Also, higher speeds can be attained when rolling, because the vehicle slows down over a longer period of time. Thus, rolling, a method of locomotion that is most efficient, will allow the user to travel greater distances due to a slower fatigue rate.

Controllabilty of the prosthesis is also of major concern. The majority of the control is provide by shifting the weight of the upper body. The knee and ankle joints, which perform these control functions in normal walking, are motionless in a wheeled prosthesis. Consequently, control must be provided from a higher location, causing both balance and maneuverability problems. A wheeled prosthesis design must therefore concern itself with a device that steers simply and without a large expenditure of energy.

The next concern asks what degree of controllability is required. A conventional prothesis user can 'steer' himself through reasonably well-trafficked areas and around a variety of obstacles. With a wheeled prostesis, at least this much maneuverability is desired. Moreover, because the rolling prosthesis is quicker than a conventional prosthesis, one could expect possibly even better mobility.

Changing terrain also restricts mobility. The ideal surface for a rolling prosthesis is flat and smooth, like a linoleum tiled floor. When negotiating a less uniform surface, problems arise for two reasons. First, the wheels are limited by their tolerance of small objects. The design must consider this constraint. Mechanically, wheels with larger radii handle objects in their path with greater ease than smaller wheels. Additionally, a suspension system would aid in traversing large bumps, as well as making the ride smoother. Secondly, there are occasions when rolling wheels are undesirable, such as when climbing stairs and steep inclines, or when traversing extremely difficult terrain. Thus, some method of locking or retracting the wheels would be appropriate. And if the knee were unlocked, a gait similar to walking could be used. This would create the possiblity to climb stairs, or to negotiate terrain that is unsafe for the wheels to roll over. In climbing steep hills, a ratchet mechanism would keep the user from rolling backwards. All of these considerations are important in making a wheeled prosthesis able to traverse the most terrain conditions for the greatest mobility.

As alluded to previously, there are two different ways of locomoting with the wheeled prosthesis, the 'walking' gait and the 'scooter' gait. The prosthesis was originally meant for the walking gait which consists of the user transferring weight from one leg to the other, pushing off with the good foot in heel to toe fashion, as in bipedal walking. After a little practice walking, however, the user would realize the possibilities of the scooter gait, wherein he pushes off on the good leg and coasts with his weight on the prosthesis. This action is a much like riding a skateboard. Higher speeds can be established, although the action does become more difficult to control. The scooter gait must be researched more carefully to design a prosthesis capable of safe, higher performance. With the proper design, this athletic gait would be attractive to many amputees who wanted to push to their physical limits. One design idea is to have the shank of the prosthesis twist and lock at 45° when the device is in coast mode. This position more closely mimics the way a skateboard is ridden, and lateral turning mobility is greatly improved.

2.3 Esthetics

One of the considerations an engineer must be sensitive to when designing for the handicapped is to help them blend in with society and live 'normal' lives. This propensity to subtlety is one of the biggest reasons people prefer artificial legs to wheelchairs or crutches. Therefore, the prosthesis should be able to camouflage itself as a normal leg. Of course, a rolling gait is going to appear somewhat different than a normal walking gait, but that is a tradeoff against improved mobility. If the leg can locomote the user as well as a normal leg, the altered gait might be permissible.

There are two main considerations in making the prosthesis look like a normal leg. First, the shape must be the same. Thus the design should probably consist of a shank, or 'leg,' connected at a joint to a 'foot'. Perhaps a shoelike covering over the wheels would lessen the strangeness of the prosthesis. Also, it would be a good idea if the wheels could lock or retract, so a normal-looking walking gait could be achieved when conditions warranted it.

3. Design Parameters

One of the problems with the original wheeled above-knee prosthesis is that it is too heavy and cumbersome. It was speculated the the device would be improved if made lighter. It would be more maneuverable not only while rolling, but also in a walking gait with the wheels locked. A lighter prototype was therefore designed and built.

The new design must still conform to the same constraints as the old one. Testing is still going to be performed by non-amputees, so the 'socket' must be designed for a good leg. It should be adjustable for different subjects' limb sizes. It needs to be able to endure pressures perhaps three times the subject's body weight, as when the user rolls off of a curb. Also, the wheel configurations and placements and the tilt of the shank must be adjustable. Additionally, one of the problems encountered in past testing of rolling prostheses is that the subject could steer by applying a torque to the thigh socket with his knee. An amputee would not be able to do this. Therefore, a more effective strapping technique is needed to eliminate movement in the thigh 'socket'. The prototype was built with these constraints in mind.

Preliminary testing was to be carried out by a 21 and a 19-year-old subject, both with skateboard riding experience, as well as experience with riding the aluminum prototype. The device was then to be tested on subjects of various size and experience in activities requiring balance.

4. Prototype design

The first prototype, designed and built for Mike Kohlbrenner's thesis, was constructed of 1 1/2" in width hollow square aluminum. The knee rested upon a U-shaped aluminum piece. This support was attached to a square aluminum 'leg', about 10 inches long, and that was connected perpendicularly to another aluminum square piece, the 'foot', approximately 15 inches long. Skateboard wheels were attached to this 'foot'. For a view of Kohlbrenner's design, see figure 4.1.

4.1 Materials

The prime consideration in the new design was its weight. The new prototype prosthesis needed to be stiff, for good control, yet light, for greater mobility. High quality hardwoods were used, since such materials are relatively light, yet stiff. Oak, mahogany, and birch were considered. The technique of lamination was used to further strengthen the wood.

Lamination consists of a number of layers of thin material glued together. When the glue dries the stiffness and strength of the material increase dramatically. It is a classic case of the whole being greater than the sum of the parts. Another excellent property of wood laminates is that the pieces can be steamed and formed into curved shapes by clamping them in a mold.

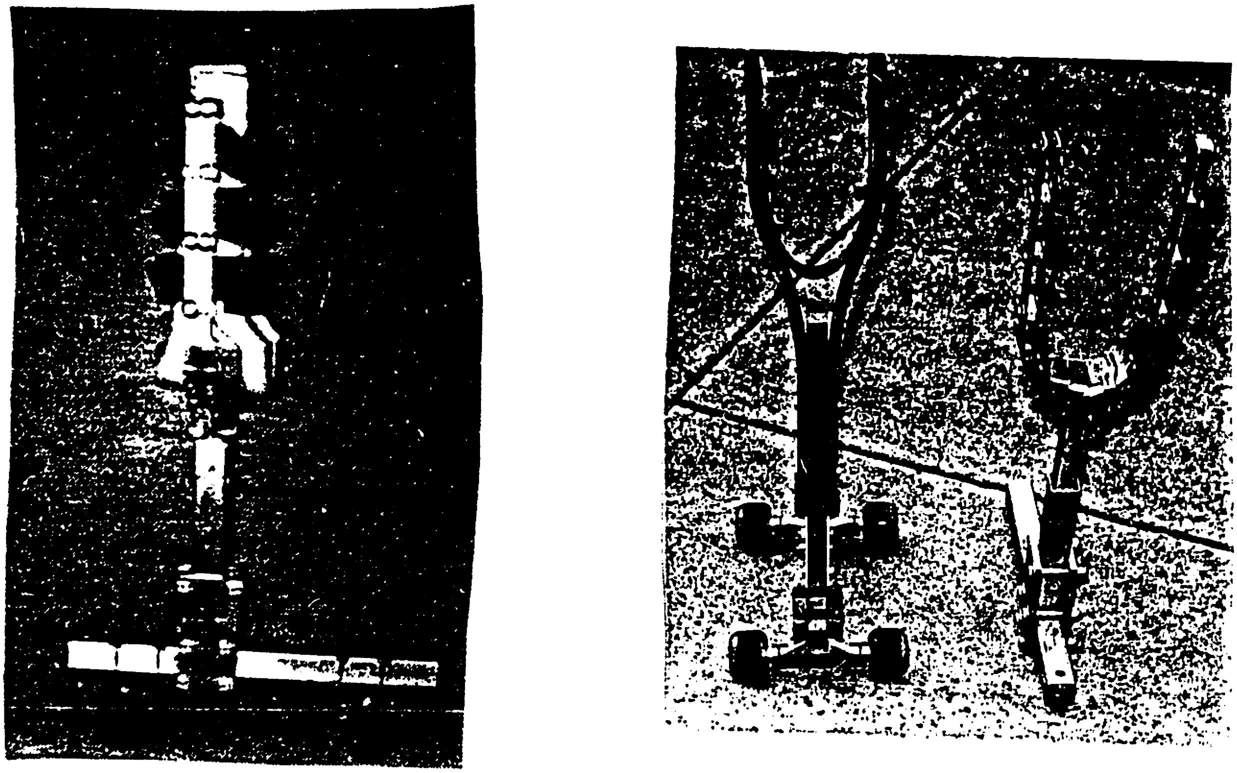


FIGURE 4.1: Michael Kohlbrenner's original prosthesis

The strips are glued and sandwiched in the mold, which is then clamped. When the glue dries, the shape is retained.

4.2 The crutch and shank

The basic design entailed a crutchlike apparatus attached to a platform to which skateboard wheels were clamped (see figure 4.2). Two long curved pieces (see figure 4.3) were constructed from laminated wood and bolted to the shank. The curved pieces were made by cutting a sheet of 1/4 inch thick louan (3 ply mahogany) into four 28 inch by 1 inch strips and gluing and clamping them to the proper shape in a lamination process.

The mold for the lamination is shown in figure 4.4. The shank (the vertical piece supporting most of the weight), was constructed of high quality oak, 1 inch by 1 inch and 15 inches long. The curved pieces were bolted through the oak with 1/4 inch machine screws 2 1/2 inches long. Holes for bolts were drilled every inch on the sides of the shank to make the device adjustable for different subjects by varying the brace height (see figure 4.5). Support for the knee was provided by a piece of canvas strapping, 1 inch in width. The ends of the strapping were bolted to the top of the curved crutch pieces, with the slack forming a cradle for the knee to rest in.

4.3 The foot

The foot of the prosthesis (see figure 4.6) was also constructed of oak, 1" by 1" by 15". There were no holes driled in it, however. The breakage of

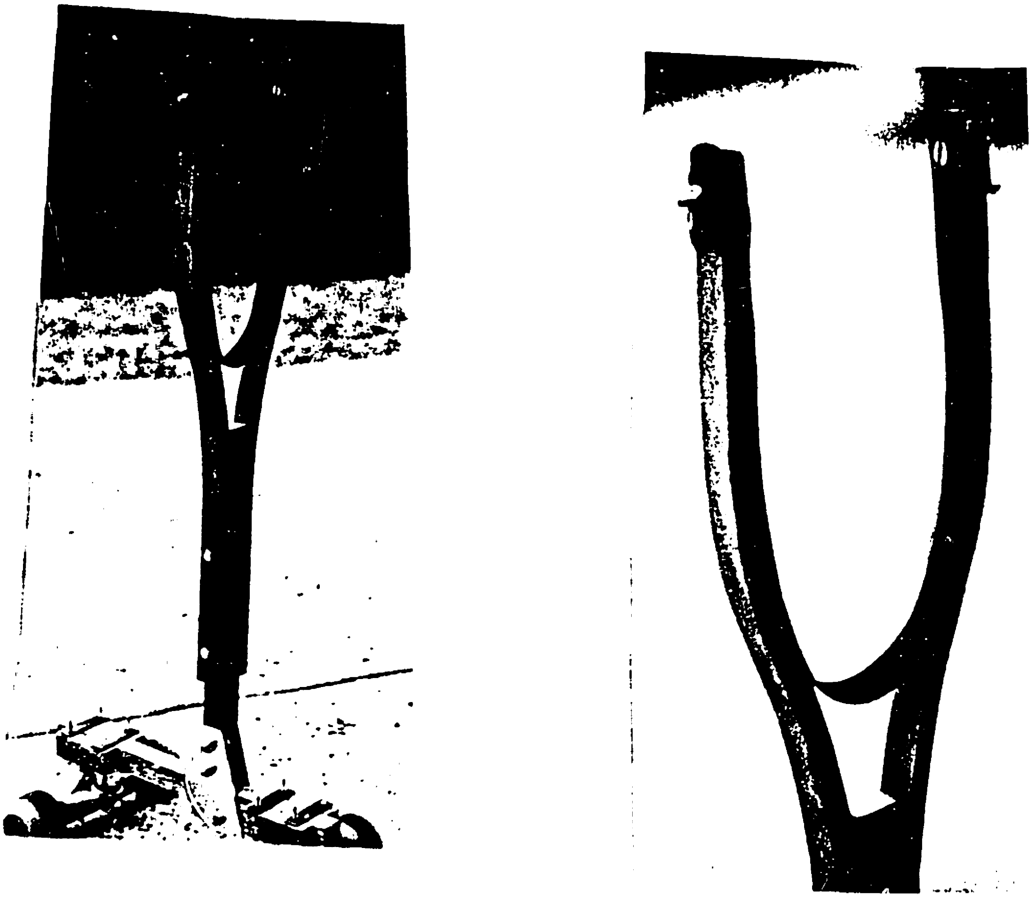


FIGURE 4.2 : The 'crutch apparatus'

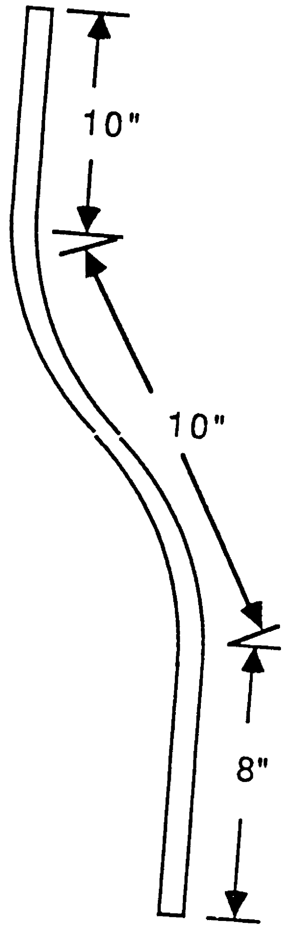


FIGURE 4.3: Detail on curved piece

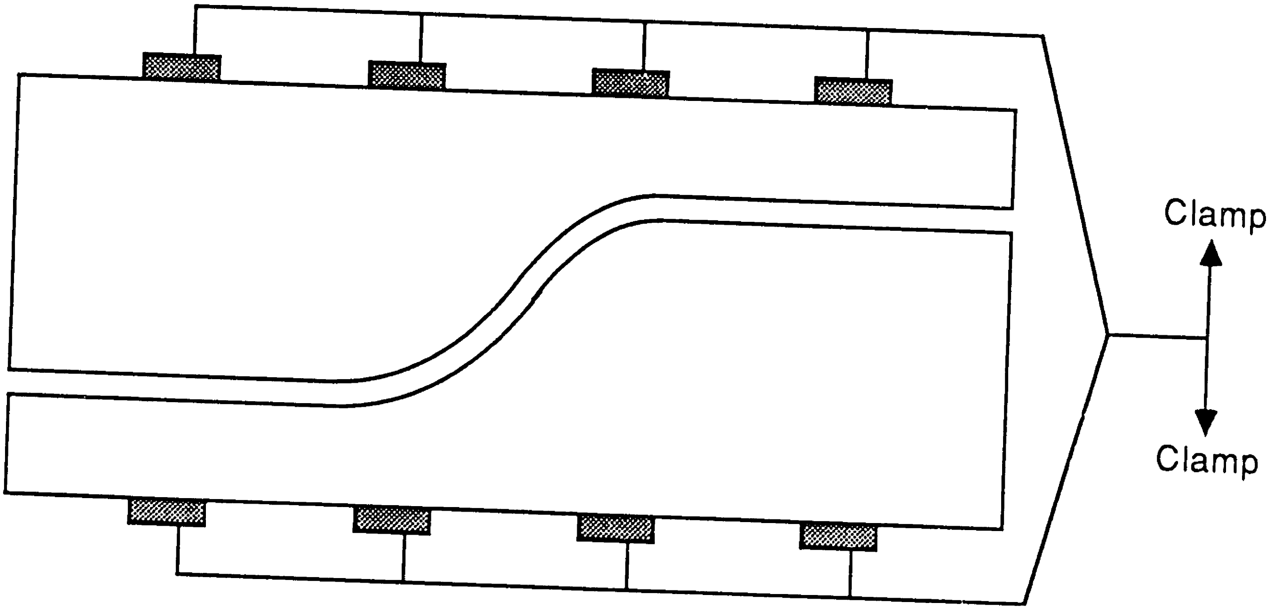


FIGURE 4.4 : Lamination mold

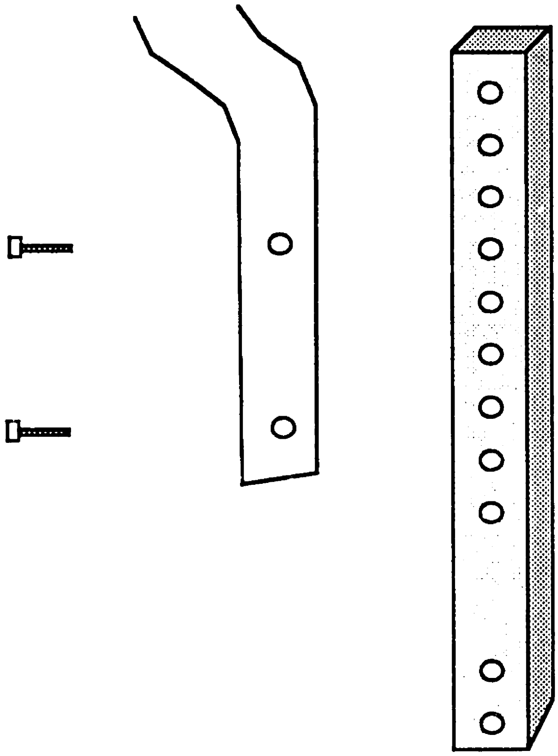


FIGURE 4.5 Height Adjustability

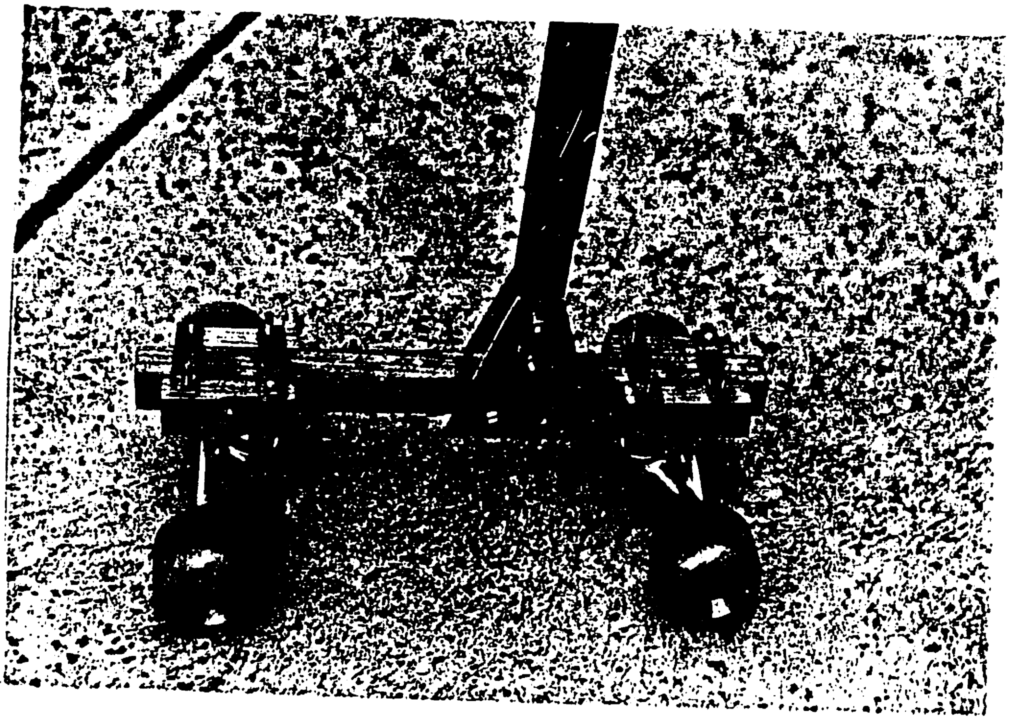
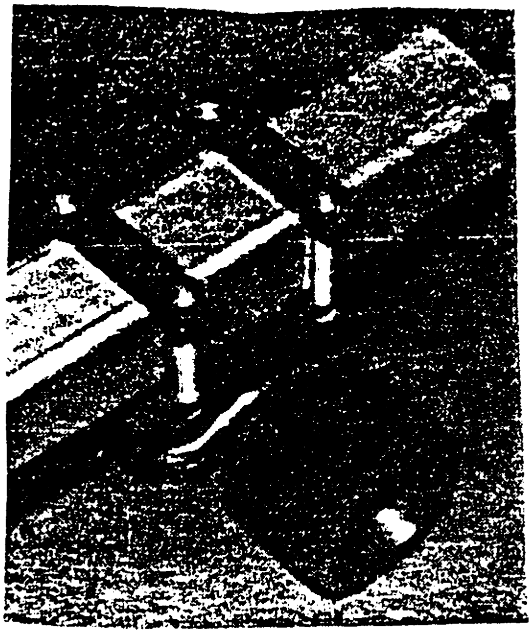


FIGURE 4.6 : The 'foot' of the prosthesis

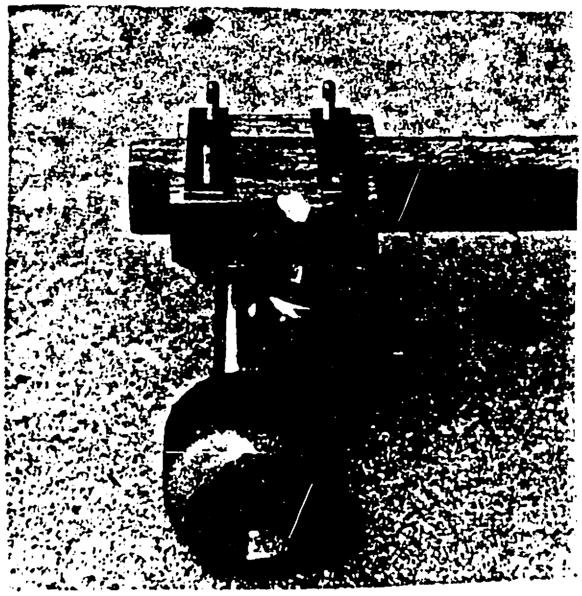
an earlier version of the design indicated that holes in the foot create serious stress concentrations. Thus, the wheels were clamped to the 'foot' instead of bolted through it. The same clamping mechanism was used on this design as in the Kohlbrenner's (see figure 4.7). The mechanism consisted of four 3/16" screws coming up through the skateboard wheel plate, straddling the oak foot, and clamping through a threaded metal bars on the other side. The clamps were too large for this prototype because the foot of the original design was 1 1/2" wide. Therefore an oak spacer was added on either side of the foot above each wheel, with the screws going through the spacers to complete the clamp. Using this mechanism, different wheel configurations can be obtained with relative ease as the screws need only be loosened, the skateboard trucks moved, and the screws retightened.

4.4 The ankle joint

The joint between the shank and the 'foot' was probably the most impressive engineering feat of the entire project. This 'ankle' joint (see figure 4.8) needs to support the weight of the subject. However, it also must be adjustable, both laterally along the shaft, and in the lean of the shank forward and back. As noted before, bolting through the foot was undesirable, as it produced stress concentrations and broke easily. Thus the joint was constructed of two aluminum plates connected through the shank. Two 5/16" inch bolts joined the plates above the foot, and two eccentric 1/4" bolts joined the plates below (see figure 4.9). The eccentric bolts were made of 1/2" aluminum cylindrical stock, one inch in

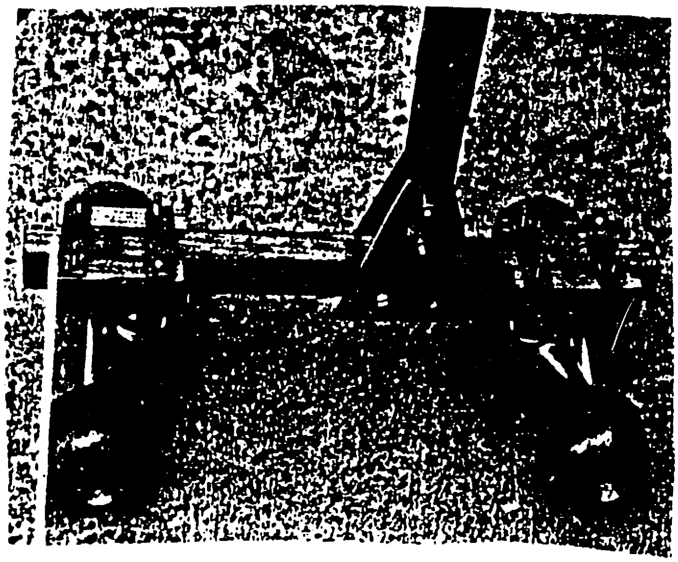


(a) On original prototype

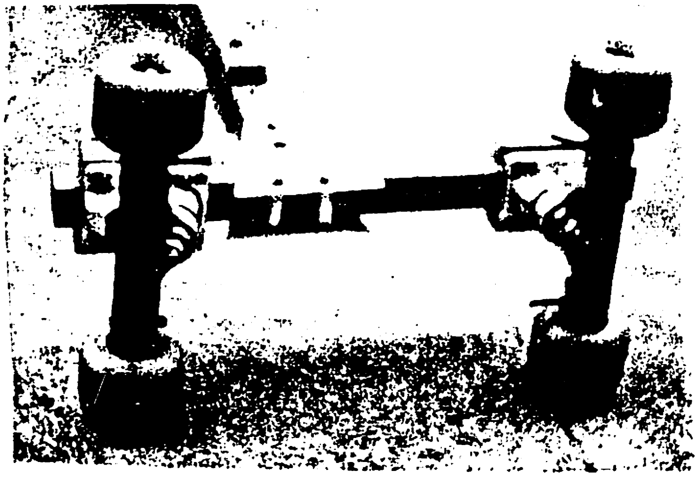


(b) On new prototype

FIGURE 4.7 : Clamping mechanism for the wheels



(a) Side view



(b) Bottom view

FIGURE 4.8 : The ankle joint

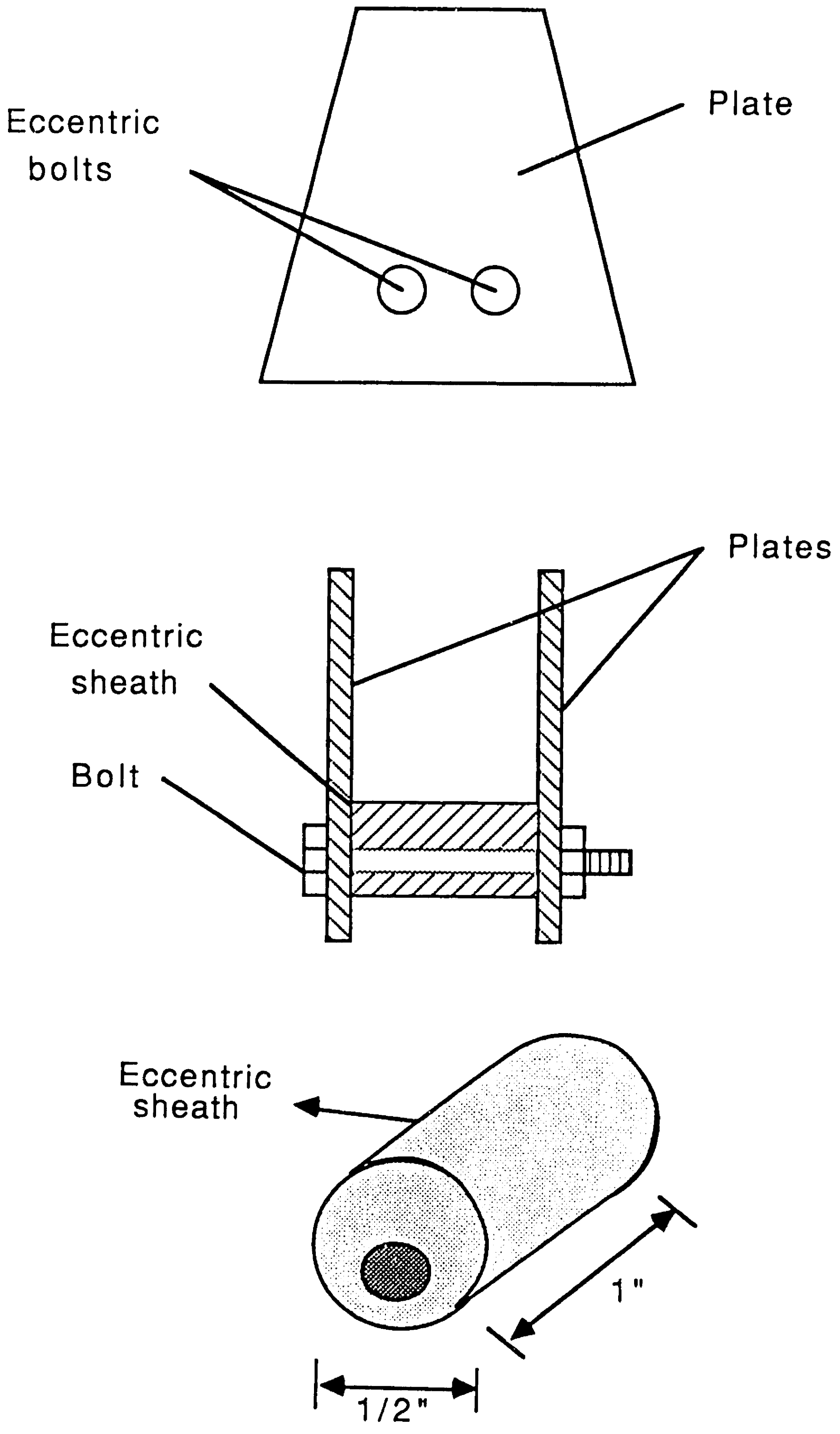


FIGURE 4.9 : Ankle joint detail

length. Using a lathe with a four jaw chuck, holes were drilled through the stock, slightly off center, to form a sheath. Standard 1/4" bolts were gnurled then coated with lock tite compound. Each bolt was then press fit through one of the plates and into a sheath, making the sheath and the bolt into a single unit with enough clearance to turn in the plate. The bolt was then secured with nuts through the opposite plate on the other side of the foot and shank.

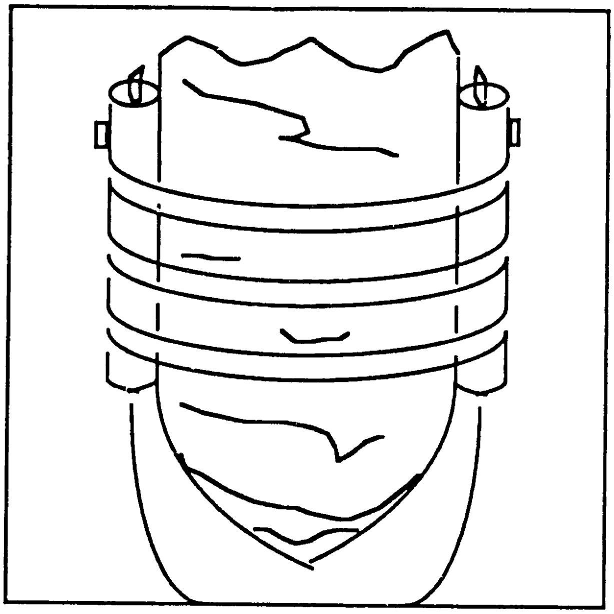
The joint functioned as follows: when the thin part of the eccentric sheath contacted the foot, the joint fit loosely and could be moved along the foot to the desired location. When in the proper position, the bolts were turned 180° so that the thick part of the sheath contacted the foot. This created a tight press that held the joint firmly in place. In this manner, the shank can be tilted fore and aft by turning one bolt more than the other, making one contact higher than the other, tilting the top part of the prosthesis.

4.5 Theoretical analysis

A large design load had to be met. Calculations of the yield stress and peak deflection were done using the models in Appendix A. An acceptable deflection for the foot was 1/2 inch which allows up to 1,000 lbs. The load the curved brace can handle is 1,200 lbs.

4.6 Strapping

The strapping functions to firmly attach the subject's leg to the prosthesis, keeping the knee rigidly fixed in the socket. The strapping was designed to be fastened to the subject before he was attached to the device, so that one subject could prepare while another was being tested. Hollow plastic tubes (actually kitchen drain pipe extenders), 1 1/2" in diameter and about 6 inches long were tightly strapped vertically to each side of the subject's leg and secured with twelve-inch velcro straps. The straps were anchored to the velcroed tubes (see figure 4.10). When the subject is securely strapped in, the tubes are slid over the curved mahogany ends of the prosthesis. The tubes are then bolted to the device by taking the bolt that holds the strapping on and putting it through a small hole drilled at the top of the plastic tube. A nut fastens the unit together, and the strapping arrangement is secured (see figure 4.11).



Fitted device

FIGURE 4.10 : Tube Detail

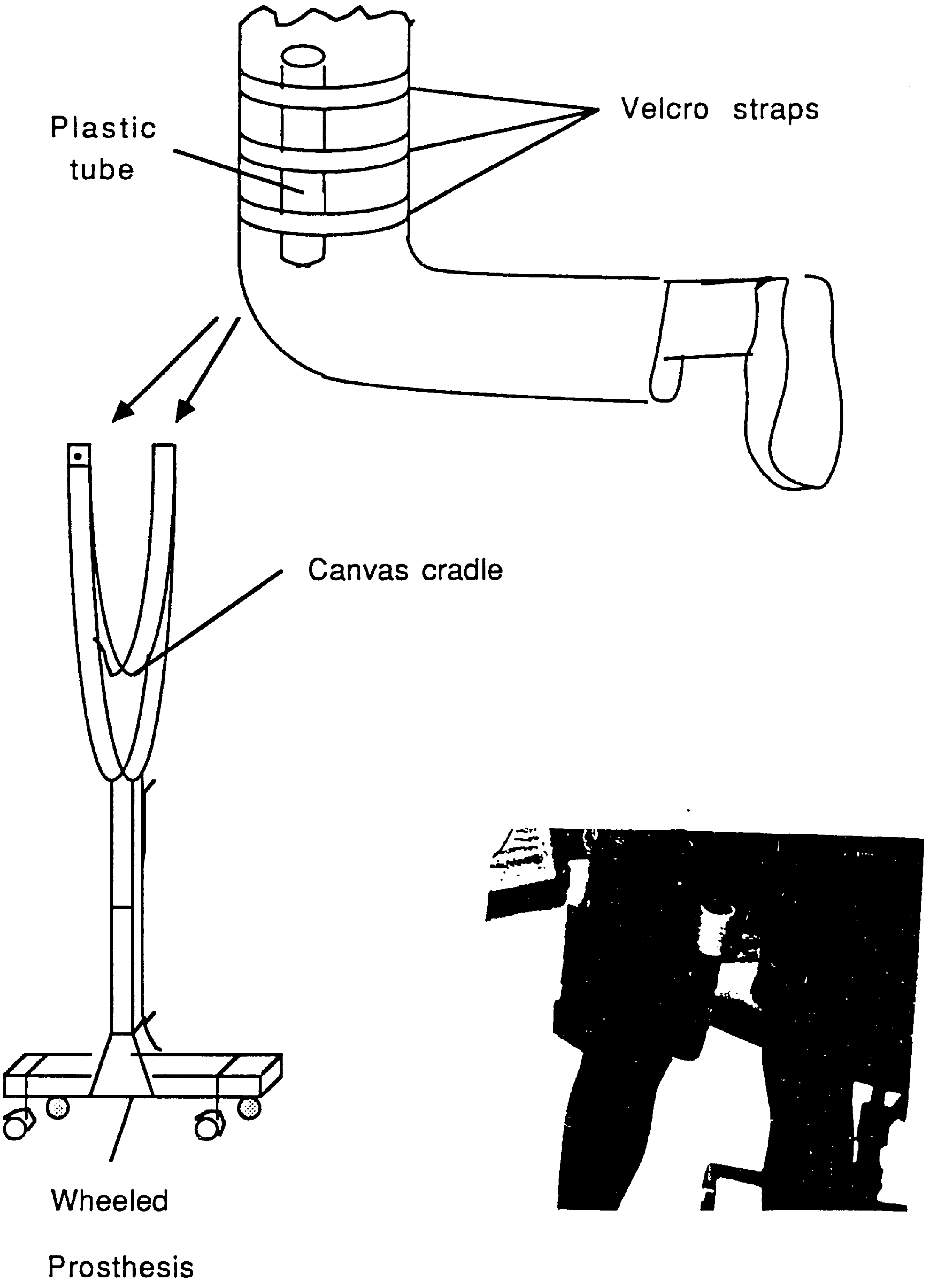


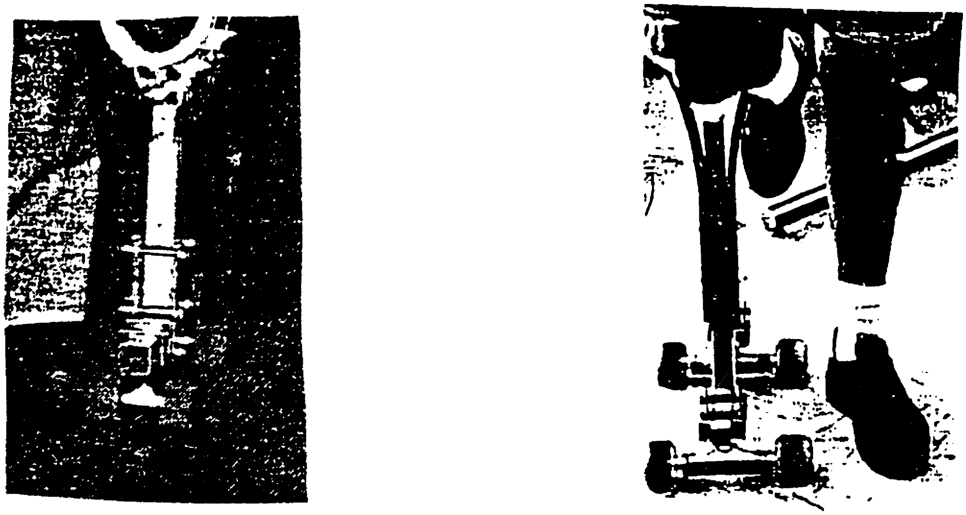
FIGURE 4.11 : Strapping in

5. Testing of the design

Before testing began, proper safety precautions were taken. The test subject wore a safety helmet and elbow pads. Also, a crutch was used for support while the subject familiarized himself with the new prototype. Because the two subjects (one of whom was the author) both had experience riding the original prototype, familiarization time was brief, and the crutch was necessary only for a short time.

One important discovery was made from preliminary testing. On the original prosthesis the wheels were fitted close together. By varying the wheelbase of the prosthesis, it was found that a wider wheel base made the device significantly more stable and maneuverable. The remainder of the tests used skateboard trucks with the wheels placed farther apart. Figure 5.1 shows the different skateboard trucks that were tested.

The testing was to consist of qualitative comparisons of the prototype's performance on various surfaces with different test subjects. The experienced subjects first travelled around a tiled room to compare qualitatively the two prototypes (see figure 5.2). After this initial testing, the leg was to be tested by other non-amputees who had no previous experience with the rolling prosthesis, however the device failed before that was possible. Test subjects complained that the canvas cradle where the knee rested was very uncomfortable. This problem was



(a) Old wheels

(b) New wheels

FIGURE 5.1 : Wheel comparison

FIGURE 5.2 : Testing a subject

remedied by adding foam padding to the contact area.

The tests indicated weaknesses in the design. The new prototype was less mobile than the original, due to the fact that the wood was less stiff than the aluminum. The added flexibility put a good deal more play in the steering. As a result, right turns were even more difficult to negotiate with the wooden prototype than with the aluminum original. The biggest dissappointment came when one of the subjects tried to simulate the peak load, putting all of his weight upon the prosthesis. Under such a load, the device failed, fracturing the oak in the shaft at the ankle joint (see figure 5.3). The wood split up through the holes drilled for the bolts, and broke.

The design did have some strong points, however. The ankle joint worked even better than anticipated. The device could be changed quickly, easily, and cleverly. Also, the strapping was easily attached and removed. The fit could have been tighter though, as balance could still be achieved with torques provided by the knee.

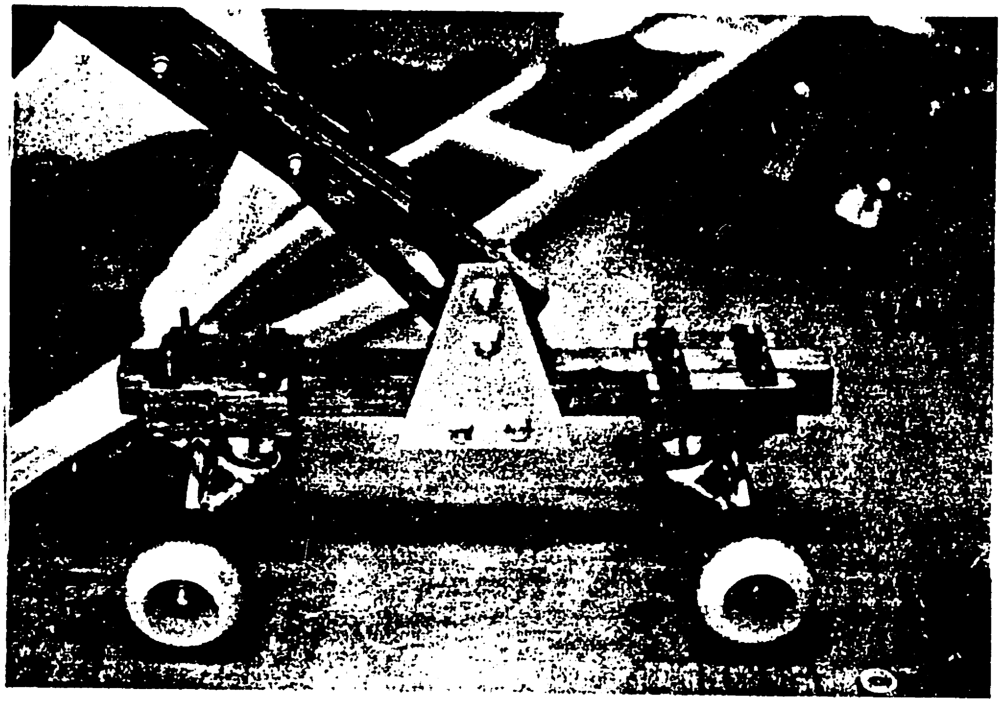


FIGURE 5.3 : The failed prosthesis

6. Discussion of Results

The new prototype's failure was disconcerting, but it did end insight into a number of areas. In terms of lightness, the new prototype was a success. It weighed half as much as the aluminum model. Also, the wood model looked sleeker and less cumbersome. Cosmetics are somewhat important to subjects and amputees alike, and the new design is more esthetically pleasing than the old one.

6.1 Improved wheelbase

First, and most importantly, we discovered a wide wheel base adds greatly to the stability of the device. Improving the devices stability enhances its controllability, consequently producing greater mobility. Improving mobility is one of the keys to proving a rolling prosthesis feasible. This result was therefore very encouraging.

6.2 Poor torsional stiffness

Wood is not stiff enough. Part of the problem lies in the nonhomogeneity of wood. Wood has grains that are stonger than other parts of it. There could be some weak points in the wood. This may be why the device split and did not actually fracture. The biggest problem turned out to be lack of torsional stiffness of the mahogany curved braces. Perhaps the wood used in the design was of poor quality, as a number of early versions of the prosthesis failed due the brittleness of the louan. Chances are, however, that almost any wood material would have a torsional stiffness problem. A laminate should be the strongest possible configuration for a given thickness of would and it was not strong enough.

6.3 Problems with mobility

Making right turns was practically impossible. Both subjects found that due to this, the lighter prototype was even less controllable than the original aluminum one. This limited mobility was a key design problem that was desired to be changed. The steering is hampered by lack of stiffness, making the response to a command slower, and damped. This makes maneuvering frustrating and difficult.

6.4 Peak load failure

The peak load failure was unfortunate. According to theoretical calculations, the shank should have been strong enough to support the load of someone rolling off of a curb. The stress concentrations produced by the holes were not taken into account however, and they can reduce the yield stress by a factor of 5 or 10. To change the design to one that would not break under the design load, it would be necessary to thicken the wood. This would increase the weight of the project, and that was the parameter that was supposed to be minimized. Another possibility is to come up with a better wood prosthesis design. Neither of the last two ideas are recommended because wood just does not perform very well. If another attempt was to be made at a lighter prototype, I would suggest a graphite composite, which can have extremely better stiffness to weight ratio as a possible material, or even aluminum in a less heavy-duty design than Mike Kohlbrenner's.

7. Recommendations and Conclusion

Mobility is the major concern in designing a wheeled prosthesis. Mobility is the major concern in designing a wheeled prosthesis. The designing and building of a lightweight prototype from oak and mahogany was an attempt to improve maneuverability of wheeled prostheses. This wood prototype, however, lacked the stiffness of its aluminum counterpart. This greater flexibility made the device only mariginally controllable. A larger problem was that the ankle joint failed at a load simulating rolling off of a curb. The stress concentrations produced by holes drilled for bolts to fasten the joint weakened the oak shank. A possible solutions could be to use thicker oak, but this takes us away from the concept of a lightweight prototype. A better solution for a lightweight prototype would be to design the rolling prosthesis using graphite or lighter aluminum than that of the original prototype.

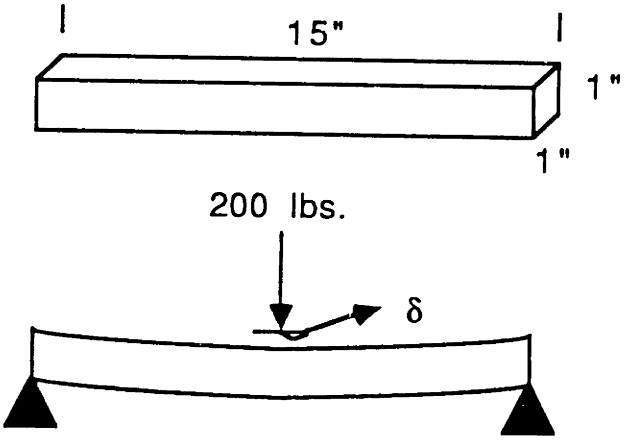
Though the wood prototype ultimately failed, much useful information was gleaned for further study of wheeled protheses. The prototype demonstrated that wheels with wider wheelbases provide greater stability and controllability and therefore, greater mobility. Additionally, the new design was remarkable adjustable. Different shank and wheel geometries could be achieved quickly with the innovative ankle joint mechanism.

As demonstrated by this study, mobility is the main issue to be studied when analyzing the feasibility of a wheeled prosthesis. After safety, mobility should be emphasized. A lightweight prototype will improve mobility, as long as it steers responsively. Further research into strong, lightweight materials and improved shaft design, as well as futher exploration of the scooter gait would result in an improved prototype of the below-knee, wheeled prosthesis.

Appendix A

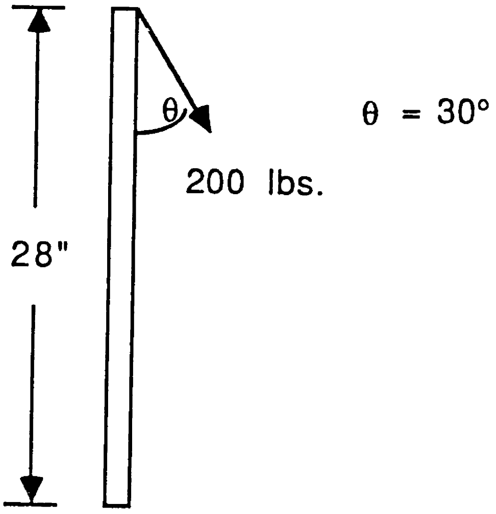
Figures For Calculations of Peak Deflection and Yield Stress

$\partial = (FL**3)/(48EI)$



Foot deflection model

$F(max) = 4My/L = (\sigma yp)I/Y$



Crutch deflection