A FEASIBILITY STUDY OF A WHEELED PROSTHESIS WITH SKATEBOARD STEERING FOR UNILATERAL ABOVE KNEE AMPUTEES

by

Michael John Kohlbrenner

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE
DEGREE OF

BACHELOR OF SCIENCE
IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1985

Signature of Author____
Department of Mechanical Engineering
May 20,1985

Certified by____
Woodie C. Flowers
Thesis Supervisor

Accepted by____
Chairman, Department Thesis Committee

A FEASIBILITY STUDY OF A WHEELED PROSTHESIS WITH SKATEBOARD STEERING FOR UNILATERAL ABOVE KNEE AMPUTEES

by

Michael John Kohlbrenner

Submitted to the Department of Mechanical Engineering
on May 20, 1985 in partial fulfillment of the
requirements for the Degree of Bachelor of Science in
Mechanical Engineering

Abstract

A study was carried out on the feasibility of the use of a wheeled prosthesis for mobility improvement in above knee (A/K) amputees. The study addressed the issues of safety, cosmetics, mobility, and control, as well as investigating possible configurations and auxiliary devices (brakes, suspensions, ratchets, etc.). Two prototype designs were built with skateboard steering and tested by non-amputee test subjects. Upper body steering was used, since an A/K amputee lacks the pivoting action provided by the ankle.

The study of the issues resulted in encouraging indications that the concept of a wheeled prosthesis was sound and warranted further study. The first prototype tested supported this. With very little skateboarding experience and average physical skills, the adaptability test subject practiced for less than one hour at simulated terrain features, and was then able to take an extended trip through interior corridors. The apparent energy cost was significantly less than a second subject who had kept pace on foot. The second prototype, which closely simulated the case of an actual A/K amputee, was then tested and the same subject made the extended trip again, with the same results.

The study concludes that the concept is feasible and that skateboard steering is safe and effective over many terrain situations. Recommendations for further research were made.

Thesis Supervisor: Woodie C. Flowers

Title: Associate Professor of Mechanical Engineering

my legs were once run over by a cadillac
the only damage was a puncture wound
now i have a small scar that itches occasionally
this is dedicated to those who weren’t as lucky

Acknowledgements

I would like to acknowledge the people who made this project possible.

First, is Prof. Woodie C. Flowers. He came up with the idea, and gave me the chance, just the right amount of guidance and several well placed kicks. Also, his performance as a test subject was greatly appreciated. Thanks to him it was a very rewarding experience.

Next, are John Murphy and Pat Ferrara of the sports equipment room, who allowed the use of safety equipment. Also from the athletic department, was Paul Grace of sports medicine, who allowed me the use of a splint. Their assistance saved time and effort, not to mention money.

Tiny Caloggero, Don Wassmouth, and Robert Samuel deserve thanks for providing assistance with the building of prototypes.

Although many people made suggestions, Jim Pappadopoulos and Rob Gustafson deserve special mention for providing especially useful help.

My brother, Dan Kohlbrenner did the photography for this report, and provided much "support" in many ways. I am lucky to have such a big brother.

My other brothers, of the Phi Sigma Kappa fraternity, merit much gratitude for allowing me to "live" at their house while producing this report and for the encouragement they offered.

I would also like to express my gratitude to all the folks at the IBM Corp. for making it possible to process all these words.

My final and warmest acknowledgements are to my parents. Along with the rest of family, they provided more love and encouragement than I had a right to expect. I don't know whether I would have done this if it weren't for them.

Table of Contents

1. Introduction

Walking, which for most people is an efficient and seemingly simple form of locomotion, is impossible for a unilateral, above-knee (A/K) amputee without the use of a prosthetic device. Even with a state-of-the-art prosthesis, the inherent complexity of the act of walking prevents the A/K amputee from achieving the level of mobility provided by normal biped walking. At best, current prostheses are a compromise, offering only limited and less energy efficient locomotion modes. Systems cannot presently be built which provide the same range of motion of the human leg, along with its capability to optimize its dynamic variables (spring constant, damping, power output,etc.) to broadly varying terrain situations. With the additional consideration of the leg's light weight and its intimate connection with the body's control, fuel supply and maintenance systems, the task becomes exceedingly difficult. Many years will pass before engineers can match the human leg developed by evolution. Indeed, it may never happen.

Another approach to the problem of A/K amputee mobility is to use a mode of locomotion other than walking. This is exemplified by the use of such things as crutches or wheelchairs, but there are limitations here also. Another possibility, which has not seen widespread use if it has been considered at all, is the attachment of wheels to the bottom of a prosthesis, allowing an efficient, rolling mode of travel. This mode of travel would be similar to that of a skateboard, with the normal leg used to push. The arms would be free--an advantage over the use of crutches or wheelchairs--and with the addition of wheel lockup to allow a walking mode, the wheeled prosthesis could be expected to give approximately the same mobility as current prostheses when encountering stairs or other such obstacles.

The purpose of this research was to investigate the feasibility of developing a device that uses wheels attached to a prosthesis to improve the mobility of unilateral, A/K amputees. This included a study of the issues involved and the testing of prototype wheeled prostheses by non-amputees. "Wheeled prosthesis," broadly defined, includes a wide variety of configurations. The scope of this research was limited to configurations involving the integration of a prosthesis with skateboard or roller skate wheels and steering systems. Steering, although not necessary, provides certain advantages in maneuverability over a device that must be lifted up to change direction.

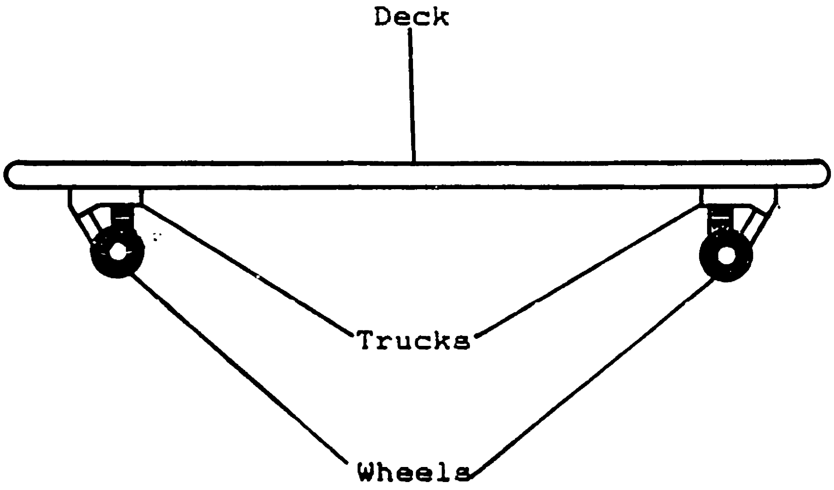
The choice of skate steering over other systems was made for several reasons. The first of these is the simplicity of its operation. Exerting a tilting moment on the skate about its longitudinal axis provides the steering action.

The second reason is that skate steering has already been developed to the point of satisfactory performance and parts are cheap and readily available. Finally, the author has ridden skateboards for transportation for over five years and that experience could be used as an advantage during the design and testing phases of the research.

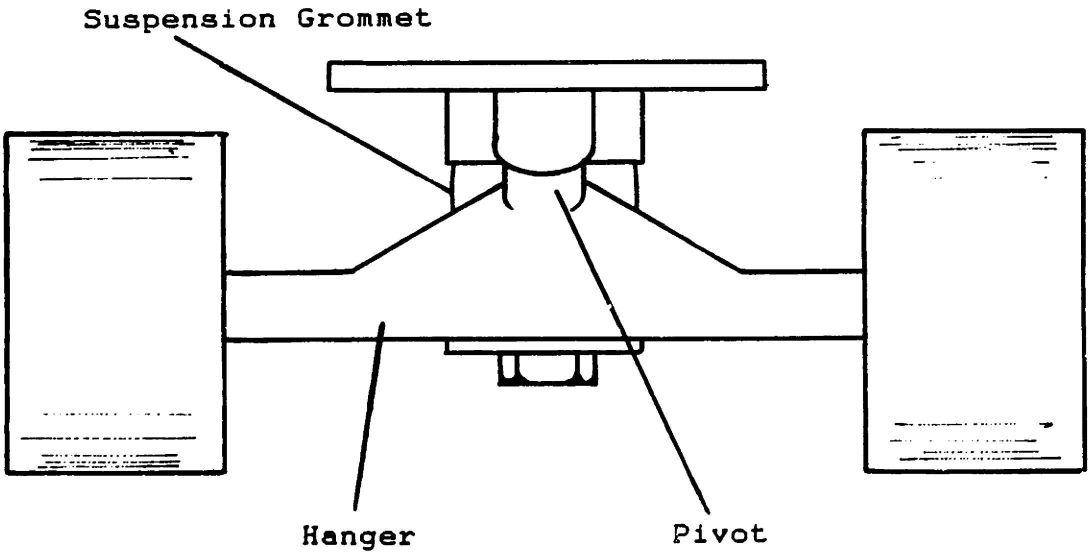
Though this research was aimed at above-knee (A/K) terminations of a single leg, the scope of application also extends through the range of less severe amputations. Further, due to the likely altering of current skate designs for this application, new designs for use by non-amputees might be developed.

2. Skate Terminology and Theory of Operation

Refer to figure 2.1 for skate terminology. Skates use pivoted-truck steering mechanisms. The wheels are attached to the hanger, which rotates on an inclined pivot. This constrains the relative motion of the hanger and deck. Since the wheels are constrained to contact the surface, tilting the deck about its longitudinal axis causes the hanger to rotate about a vertical axis. Two trucks are attached to the ends of the deck with opposing pivot angles so that they rotate in opposite directions. This causes the skate to turn around a center of curvature located at the intersection of



a) Skate parts



b) Truck detail

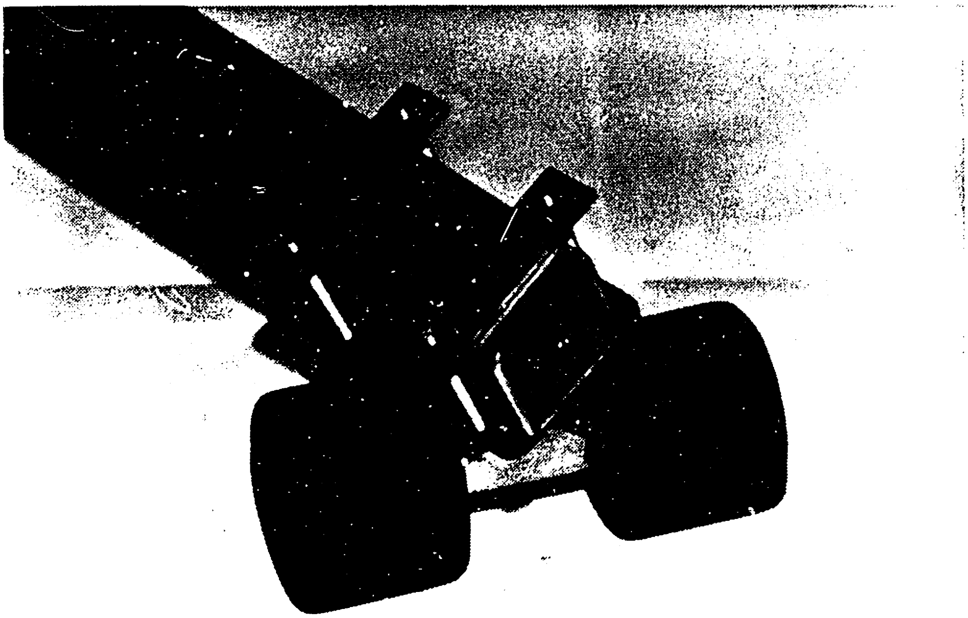
Figure 2.1: Skate Terminology

lines extended along the axes of the two axles. See figure 2.2.

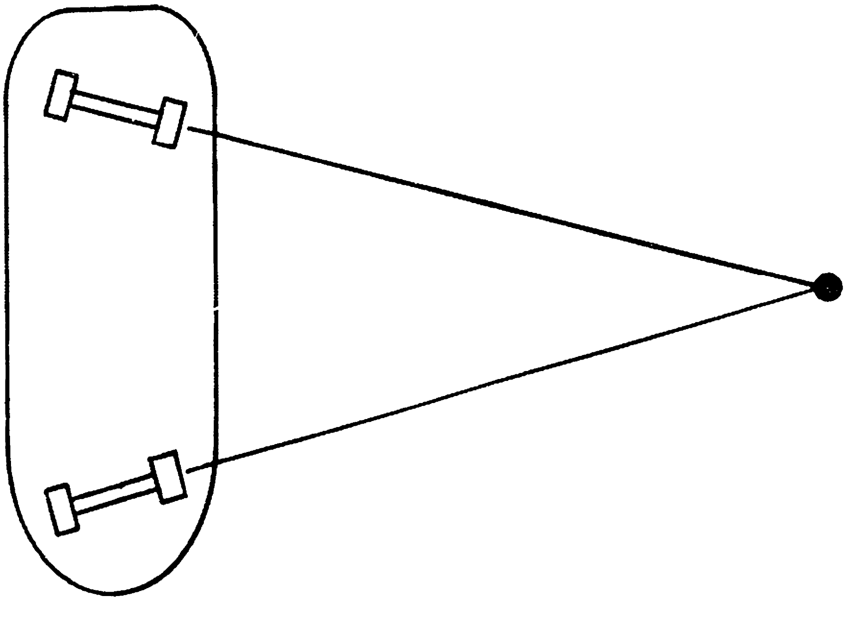
3. Issues

3.1. Safety

Issues addressed in this study included the safety, cosmetics, control and configuration possibilities of wheeled prostheses, as well as the actual amount of increased mobility provided. The safety issue is of paramount importance since an unsafe device would have little value to an A/K amputee, no matter how much mobility it provided. The use of skates in general is more dangerous than normal walking, due to the problems associated with free-rolling wheels, the sensitivity of small wheels to small obstacles and the higher speeds. Since the wheeled prosthesis is intended for low speeds, however, this last consideration can be discounted. It is also possible that a newly developed design might present a greater risk than conventional skates as a result of its special configuration requirements. This could arise out of the A/K amputee's lack of an ankle and knee, which play a large part in the control of conventional skates. If a wheeled prosthesis can be developed that provides a significant mobility improvement, it is likely that many A/K amputees would be willing to accept a risk



a) Turning truck



b) Illustration of turning skate with center of curvature

Figure 2.2: Skate Steering Operation

level on the order of that associated with skates. Further, with proper training and responsible riding, these risks can be minimized, and with the use of safety devices, the risk of injury in the event of an accident can also be minimized. Evidence indicates that this is the case. The vast majority of injuries that the author has sustained or witnessed have occurred in situations where the rider pushes his/her skill limits or in those involving high speed without the use of sufficient safety equipment.

Another related issue is whether riding a wheeled prosthesis will be safe for surrounding pedestrians and whether these pedestrians will perceive the activity as being safe for themselves. The author's experience with skateboard riding amid pedestrians has shown that many people feel that there is a significant risk of collision involved in this activity. This is due in some part to the bad reputation attained by skateboards before the technology advanced to the point where they were safe. These feelings are somewhat justified, however, since skaters have the propensity to travel at speeds greater than walking speed and a collision with a pedestrian could certainly cause an injury. Further, since a skateboard is not attached to the rider, the possibility of a runaway skate exists and quick side-to-side evasive maneuvers are difficult. In the case of a wheeled prosthesis, where the speeds are low and the skate is attached, the only danger for surrounding pedestrians is if the A/K amputee loses control while close enough to another person to cause a low speed collision. Clearly, the burden of responsibility for keeping this activity safe would be on the shoulders of the A/K amputee, but again, with proper training and responsible riding, these risks could be minimized. Within the author's experience, most collisions that have occurred between pedestrians and skate riders or their skates would not have occurred if these practices had been followed.

3.2. Cosmetics

Cosmetics is an issue that arises with all prostheses. A goal of most leg prostheses is to provide a natural gait and leg appearance. Obviously, a wheeled prosthesis will not provide a natural gait. It may be possible, however, to design a small enough wheel assembly or one that can be recessed, so that the foot appearance will not be overly abnormal. Also, as will be discussed below, a possible configuration would be a scooter that would not be integral to the prosthesis but ridden. Although the gait here would still be unnatural, the leg appearance concerns would be restricted to the conventional prosthesis. As with the involved risks, if a wheeled prosthesis provides enough of a mobility improvement, it is likely that many A/K amputees would tolerate the unnatural appearance.

3.3. Mobility

Mobility can be quantified in terms of energy or time required to traverse a distance or defined simply as the ability to travel over a given terrain. The mobility improvement foreseen in the use of a wheeled prosthesis will allow an A/K amputee to travel over smooth (relative to wheel radius) terrain, using a rolling mode of locomotion. This applies to gentle slopes as well as level surfaces and is not prevented by small obstacles (with some skill, skate riders can ride over obstacles as tall as approximately one half the wheel radius). It is also foreseen that both the energy cost and speed capabilities involved in the use of a wheeled prosthesis on this terrain will be improved over those involved in using conventional prostheses, as long as the terrain is relatively free of obstacles. They could even be an improvement relative to normal human walking. The author's skateboard riding experience supports this. Further, the wheeled prosthesis will have a non-rolling mode that would allow the A/K amputee to overcome larger obstacles (curbs, stairs, thick carpets,etc.). It is expected that the wheeled prosthesis used in non-rolling mode will have energy costs and speed capabilities equivalent to those of conventional prostheses. A design providing an efficient non-rolling mode in addition to the rolling mode would be relatively complex, since the wheels would have to be locked up in this mode. The transition between the two modes is also of concern, and it is expected that a good design could provide a simple and rapid transition.

The energy costs of human walking are due not only to providing propulsive power, but involve also the complex kinematics involved. Energy is used (and dissipated) in providing leg motion, and the horizontal and vertical oscillations of the C.G. as well as arm swing all require energy input. Much study has been done on this subject and more thorough discussions exist in biomechanics literature. The wheeled prosthesis can potentially improve energy cost in two ways. The first of these is by reducing the mechanical energy output required to traverse a distance. Rolling elements allow the use of momentum to provide efficient coasting, while the ability to "coast" during walking is limited, since to "coast" without falling requires taking more steps. If there is no power output during these steps, they are purely dissipative, at a much higher rate than that provided by rolling elements. Keeping pace with a person walking while riding a skateboard on a level, smooth (relative to wheel radius) surface generally requires a single push no more often than for every 10-15 strides of the walker. The rolling resistance (aerodynamic drag of the rider is small and equal to that in walking at equal speeds) of rolling elements depends on the quality and size of the bearings and wheels and upon the characteristics of the riding surface. The small size of skate wheels increases their rolling resistance over that of larger wheels, as well as making them more affected by smaller obstacles. Also affecting rolling resistance is the ratio of the radius of application of the bearing drag force over the wheel radius. Another factor is the interface between the wheel and the surface. Softer and rougher surfaces and softer wheels all increase the rolling resistance.

The second way that a wheeled prosthesis might improve energy cost is by improving the mechanical efficiency in producing useful work. Since the wheeled prosthesis can always be relied on to bear the weight of the A/K amputee, the force output required from the pushing leg can be optimized to the vector sum of the horizontal propulsive force and the minimum vertical force required to maintain traction between the pushing foot and the ground. This mode, to be known as "traction-limit pushing," would be more efficient than one where the wheeled prosthesis is lifted off the ground during the push stroke, to be known as "step-into pushing." During step-into pushing, vertical C.G. motions would be present which are similar to those in walking and would result in increased energy cost.

3.4 Control without ankle/knee

Because an A/K amputee lacks an ankle and a knee, compensation must be made in the skate steering system. Figure 3.1 shows a free body diagram of a skate/rider system

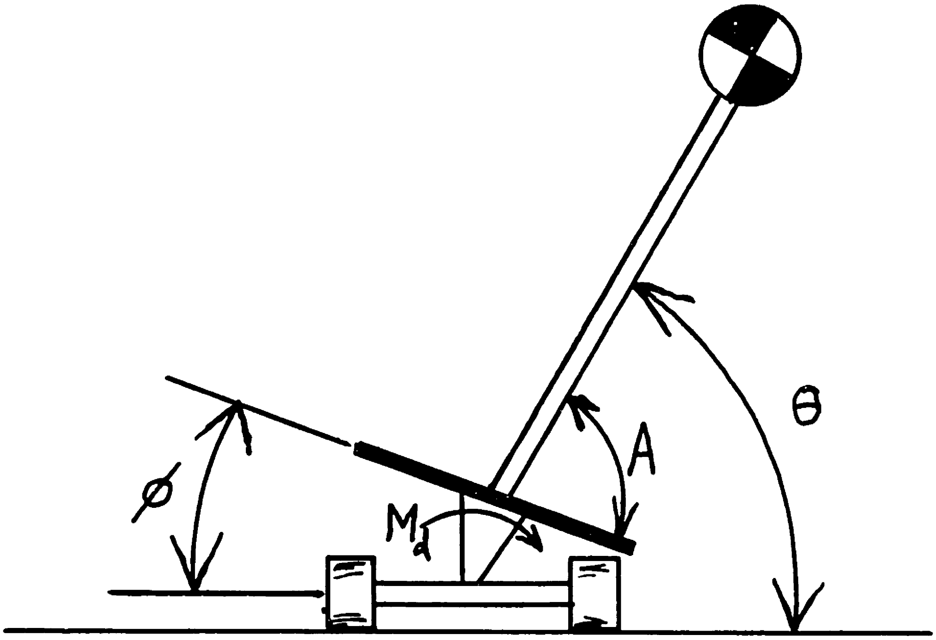


Figure 3.1: Free Body Drawing of Skate/Rider System in a Turn, Showing Associated Angles

in a turn. As mentioned above, steering a skate requires that the rider exert a moment, M_d, on the deck in order to overcome the compliance of the truck suspension and tilt the deck through an angle relative to the axle, ϕ. This rotates the two trucks about their vertical axes (see figure 2.2). The line connecting the C.G. and the center of the deck is at an angle, θ, with respect to the ground. The angle, θ, is given by:

$$\theta = \arctan[g/(V^2/R)] \tag{1}$$

where:

θ = lean angle

g = gravitational acceleration

V = velocity

R = radius of curvature of the turn.

The angle, A, is given by:

$$A = \theta + \phi \tag{2}$$

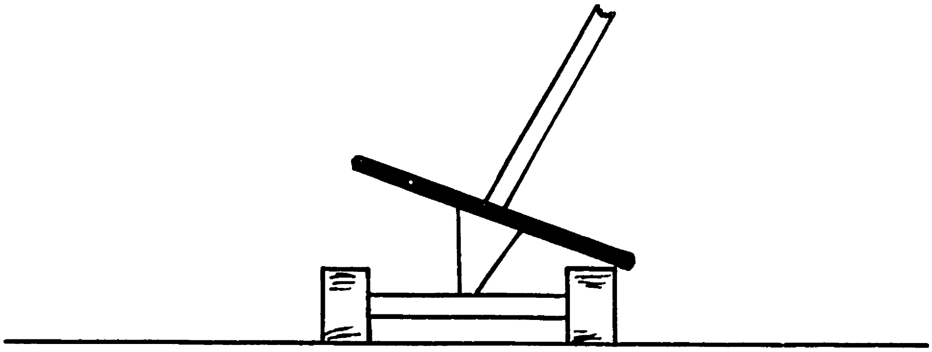
where:

A = "ankle angle".

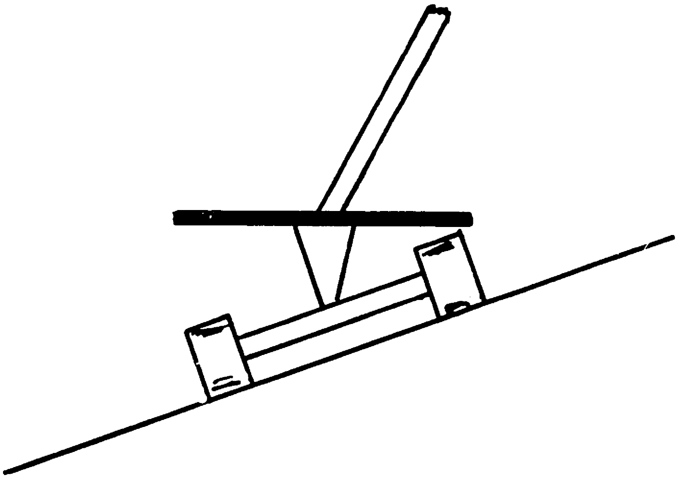
Since the radius of curvature, R, is a function of the deck tilt angle, ϕ, equations 1 and 2 show that the "ankle angle," A, varies with velocity for a given deck tilt angle, ϕ. The rider's ankle normally provides the deck moment, M_d, and the compensation for variations in the "ankle angle", A. Also, the ankle normally provides compensation for irregularities in the terrain which lift the wheels on one side of the skate. Here, the skate should not deviate from its path, so that the deck moment, M_d, the lean angle, θ, and the deck tilt angle relative to the axle, ϕ, should remain constant (this assumes small turning rates). However, since the deck angle relative to the surface, B, changes, the "ankle angle," A must change. See figure 3.2. In normal skate riding, the pivoting and moment functions are provided by the ankle. In the case of an A/K amputee, there is no ankle, so that these functions must be provided by an alternate method. There are two categories of solutions to this problem. One is to use upper body steering and the other is to use an auxiliary steering system.

Upper body steering involves a rigid attachment between the skate and leg parts of the wheeled prosthesis. Moments are easily transmitted through this junction, but it cannot pivot. Hence, to allow variable leaning of the C.G., the rider must lean with the upper body, pivoting at the hip. See figure 3.3. This is limited by discomfort at large lean angles, but the range should be sufficient for low speeds. There is also the question of control and the effect of irregularities on the system. This was one of the main issues addressed in the prototype experiments.

In an auxiliary steering system, the deck moment is provided by an auxiliary mechanism and there is a pivoted junction between the skate and leg parts of the prosthesis. This pivot may be sprung to help with balance. A



a) Surface flat



b) Surface slanted

Figure 3.2: Free Body Drawings of Skate/Rider System in a Turn, Showing Effect of Surface Irregularity

disadvantage here is that steering inputs may require the use of an upper limb, limiting its freedom. The most obvious form of auxiliary steering system is a post attached to the front of the skate. See figure 3.4. This is the concept involved in the scooter configuration mentioned above.

The lack of a knee in an A/K amputee presents other problems. The complex suspension provided by the human knee cannot be copied in the wheeled prosthesis. However, a vertical shock absorption mechanism may be necessary for a comfortable ride and could be incorporated into the leg of the prosthesis. Another consideration is that long stroke pushing requires vertical motion of the torso to maintain contact between the pushing foot and ground. Also, hard braking with the pushing foot (discussed below) tends to require that the contact with the ground be made a distance behind the skate, in order to maintain stability. The low speeds of the wheeled prosthesis may eliminate any need for either long stroke pushing or hard braking, so a vertical shock absorber may be all that is required. This could be as simple as thick cushioning at the load bearing point.

3.5 Brakes/lockup/ratchets

The use of rolling elements suggests that a braking system may be desirable. This could be in the form of variable brakes for deceleration or a lockup feature for use during the non-rolling mode. A related system is a ratchet

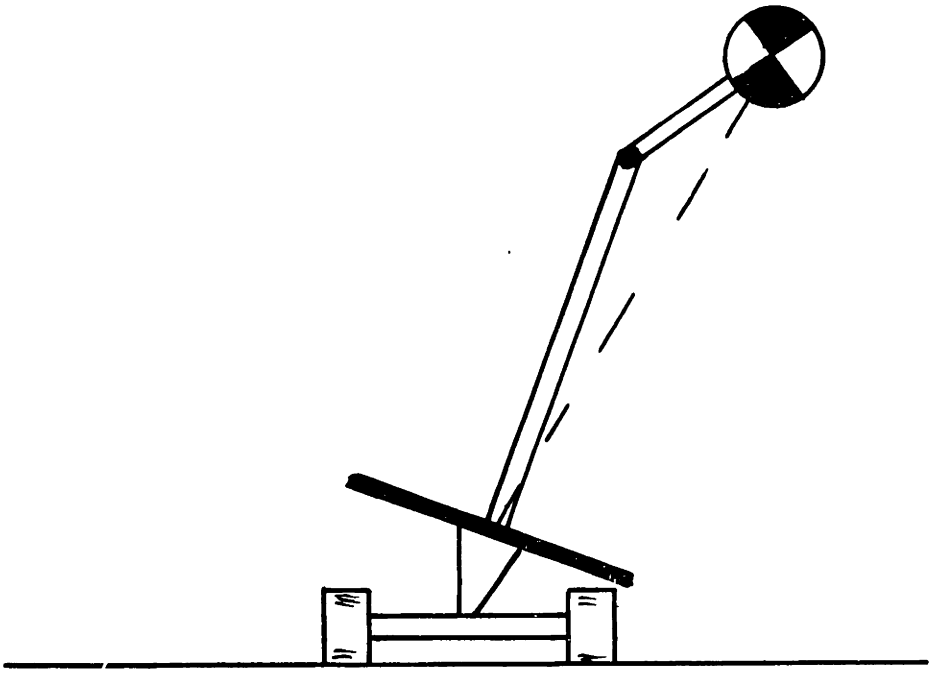


Figure 3.3: Free Body Drawing of Upper Body Steering

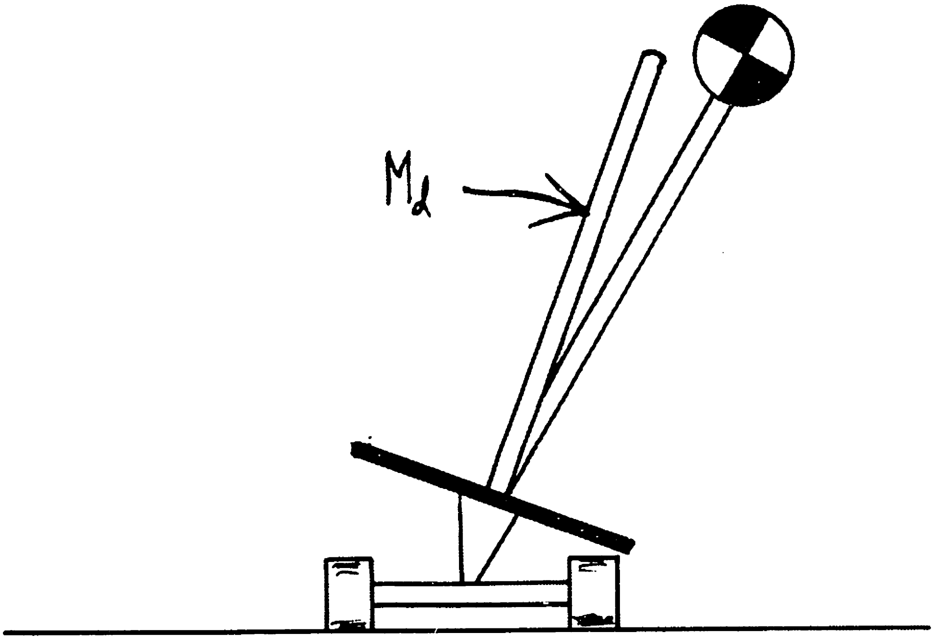


Figure 3.4: Free Body Drawing of Auxiliary Steering

or one-way clutch that would aid in ascending ramps or stairs.

While riding a skateboard, dragging the pushing foot on the ground provides effective deceleration. If this method can be applied to the wheeled prosthesis, there will not be a definite need for mechanical brakes. If it is decided that mechanical brakes are to be used, there are several issues that must be considered. The first is that skate wheels were not designed to transmit torque across the junction between their nylon cores and the outer polyurethane layer. Either specially designed wheels or a method of applying braking torque directly to the polyurethane is needed. Next, if there is to be proportional actuator feedback, there is the option of whether the default case of the brakes is on or off. If variable braking and lockup are combined in the same system, a default case of brakes locked gives the safety of requiring an active control input to enter rolling mode. However, it also presents the possibility of forward pitching if actuator force is accidentally relaxed. A simple compromise is a system with a default case of brakes off and an actuator that can be locked in its full on position.

As mentioned, brakes used for deceleration present the problem of the rider pitching forward when the brakes are applied suddenly. The rider will be prone to this since the wheeled prosthesis will have a short wheelbase relative to the moment of inertia of the rider, measured about the contact points of the front wheels. There are several possible solutions to this problem, one of which entails braking only the rear wheels. If the brakes are applied too hard, the weight transfer onto the front wheels will decrease the braking power of the rear wheels. The success of this method depends on the amount of forward pitching required to effectively decrease the braking power. Too much weight on the front wheels makes the system very sensitive to small obstacles. The combination of hard rear wheel braking and a pebble might easily cause pitching.

Another potential solution to the problem of braking induced pitching is a system in which the brakes are activated by leaning backward. This system should be easy to tune to provide effective braking power reduction without adverse forward leaning. Another potential problem arises, however. The level of stability in skate steering is decreased when the C.G. is moved backward. It is likely that this effect will not be pronounced at the low speeds that the wheeled prosthesis is intended for. Also, if this actuation system is coupled with rear wheel braking, instability of this type may be cancelled by the pendulum stability provided by the braking force acting on the rear wheels.

If it is decided to dispense with brakes, it will still be desirable to have a lockup for the non-rolling mode. Since modern skate wheels are generally made of polyurethane, lockup would provide relatively high traction for the end of the prosthesis during this mode. However, this traction does suffer significantly from wetness on the ground (it is not advisable to use the rolling mode during wet conditions for this reason and since skate bearings wear faster if the grease is washed out). If there is not a safe amount of traction during wet conditions, it may be necessary to activate an additional surface during lockup to provide sufficient wet traction for the non-rolling mode. A system in which the wheels recess into a hollow prosthesis shoe, leaving a shoe sole to walk on, would yield the additional benefit of providing a cosmetic system during non-rolling mode.

A ratchet or one way clutch would aid in ascending ramps or stairs by disallowing backward rolling (this would not assist in descending stairs). With attached, free-rolling wheels, the safe method of ascending or descending stairs involves side-stepping, since rolling off a stair would be hazardous. For the purpose of ascending stairs, a ratchet would only be desirable in the absence of a lockup feature. In ascending steep ramps, however, a ratchet would be useful even in the presence of a lockup feature. A disadvantage of a ratchet is that it would limit mobility in certain situations where backward rolling would be desirable.

3.6. Configuration possibilities

The wheeled prosthesis could be either an integral leg/skate system or a device with wheels that is ridden. The prototype built for this investigation falls into the first category. One variable here involves the steering system. There are single track roller skates on the market that are ridden like ice skates. A prosthesis with this setup could be made simple and compact, but would require stem christies to change direction. Another integral skate/leg design is one where rolling mode is activated by inserting a special cane into the skate. The cane could then be used as an auxiliary steering system.

A device that is ridden offers the advantage of a separate prosthesis and skate assembly. This simplifies leg design and gives a more cosmetic prosthesis. A "scooter cane" could be designed which acts as a cane during non-rolling mode. To enter rolling mode, the skate assembly would be activated and then stepped on with the prosthesis. Another design that would be ridden is one that had a seat, perhaps similar to the modern chairs that have an inclined seat and a platform for knee support. Any one of these wheeled designs could also be provided with a small, battery powered electric motor.

4. Issues Addressed and Constraints in Device Testing

There were two successive prototypes that were built for testing. These devices were not actual prostheses, since the test subjects for this research were not amputees. The first device was a simple design that immobilized the ankle and knee in order to check the feasibility of upper body leaning as the input in skate steering. The device was also used to obtain information to help in designing the second device. The second prototype more closely approximated the case of an A/K amputee using a wheeled prosthesis, so that the safety, control, comfort and energy issues could be checked. Also, it allowed for adjustments of several geometric variables to establish guidelines for optimization of the design. Further, the device could be easily modified to check such things as scooter steering. The second prototype differed from an actual wheeled prosthesis as a result of the non-amputee test subjects. The lower leg of the rider had to be bent back and the device was strapped to the thigh. Kneeling support was used, which also departs slightly from the case of an A/K amputee.

Since the author has substantial experience riding skateboards, it was necessary to have a second subject who had no experience so that the adaptability to a wheeled prosthesis could be assessed. The research supervisor, a 41 year old male, volunteered for this position.

5. Experimental Apparatus

5.1. Safety Harness

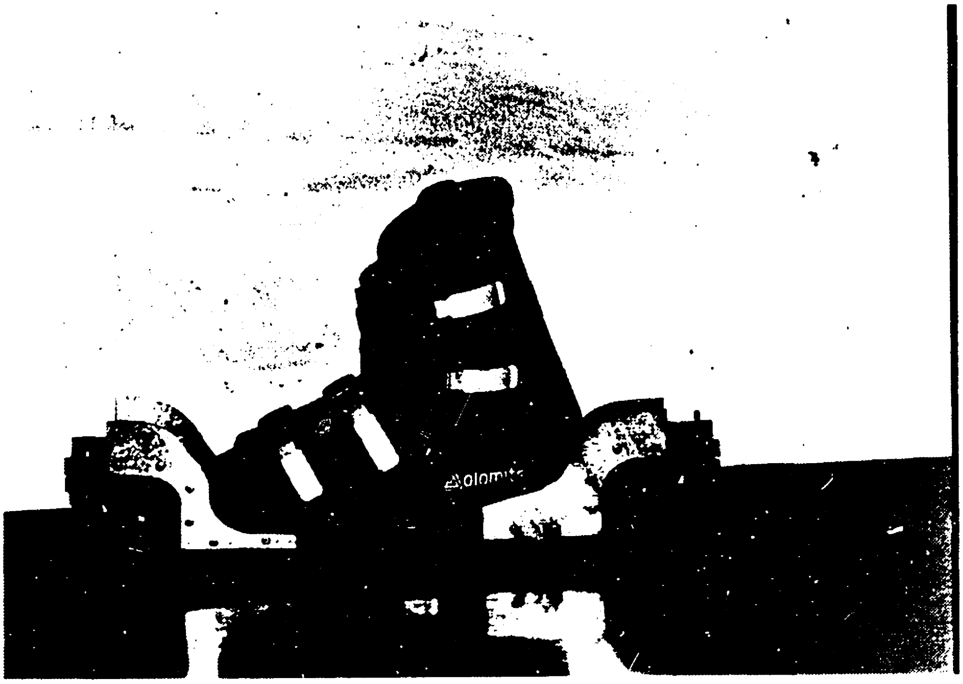
During testing, safety had to be ensured. Since the subjects had to ride devices of unknown safety with some of the normally available control removed, a safety harness was built. This consisted of a body harness suspended from an overhead trolley 10 ft. above a smooth linoleum riding surface. This rode in a straight track that provided a useable floor area approximately 30 ft. long by 10 ft. wide. This was sufficient for the purposes of these tests. The harness was constructed out of mountain climbing equipment and had two parts. The lower "diaper" harness carried most of the weight with straps around the upper thighs and one around the small of the back. The suspension rope attached in front, at waist level. The upper chest harness had a strap around the back and over one shoulder and a loop at mid-chest level. The suspension rope was fed through the loop, keeping the subject vertical when suspended.

5.2. First Prototype

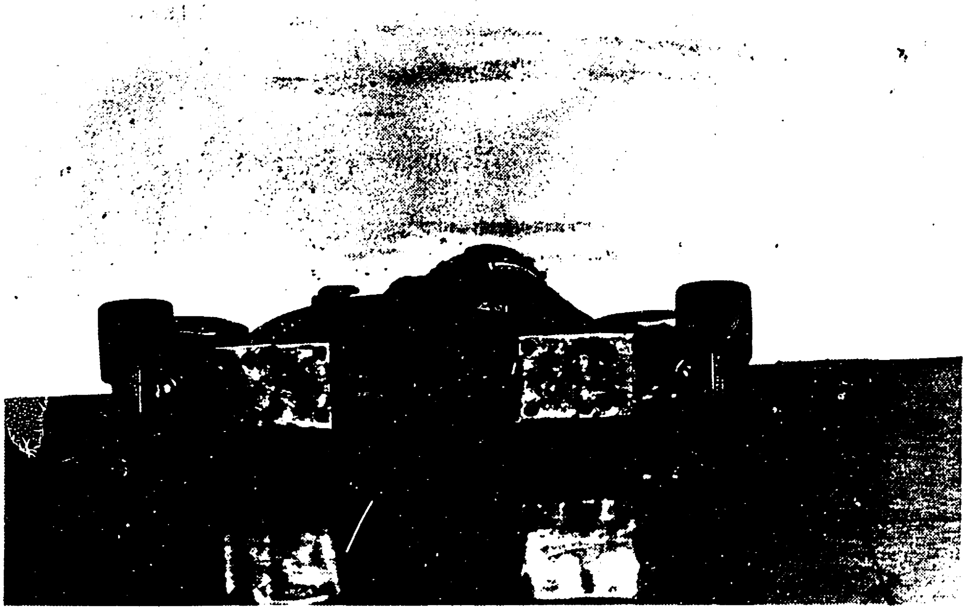
The main constraint guiding the design of the first prototype prosthesis was that the ankle and knee of a non-amputee test subject had to be immobilized to make a first approximation of an A/K amputation. It was also desirable to have a low slung skate so that the height differential of the two feet was not excessive. The minimum differential attainable was governed by the thickness of the skate structure under the foot, the ground clearance needed, and the clearance needed for tilting of the skate during turning.

The design was based on the use of a ski boot for ankle immobilization and a splint for knee immobilization. See figure 5.1. Trucks were attached to the ski boot by means of two "Z-couplers". See figure 5.2. This resulted in a height differential of approximately 1-1/2 in. and a wheelbase of 18 in.

The design was sufficient to test the concept and check upper body steering. There were several problems, however. The front Z-coupler was prone to flexing since the reinforcements could not be as large as in the rear because of interference with the boot. This prevented the full forward leaning desired for stability. There was also a slight misalignment in the trucks, causing the prototype to pull to one side when standing upright on the skate. To compensate, the rider had to lean in the opposite direction. This caused a slightly uncomfortable posture. Also, the wheelbase was too long so that the turning radius was too large, limiting maneuverability. Neither the ski boot nor the knee splint was sufficiently rigid to prevent some use



a) Skate, side view



b) Skate, view of bottom

Figure 5.1: First Prototype

c) First prototype fitted to subject

Figure 5.1 cont.: First Prototype

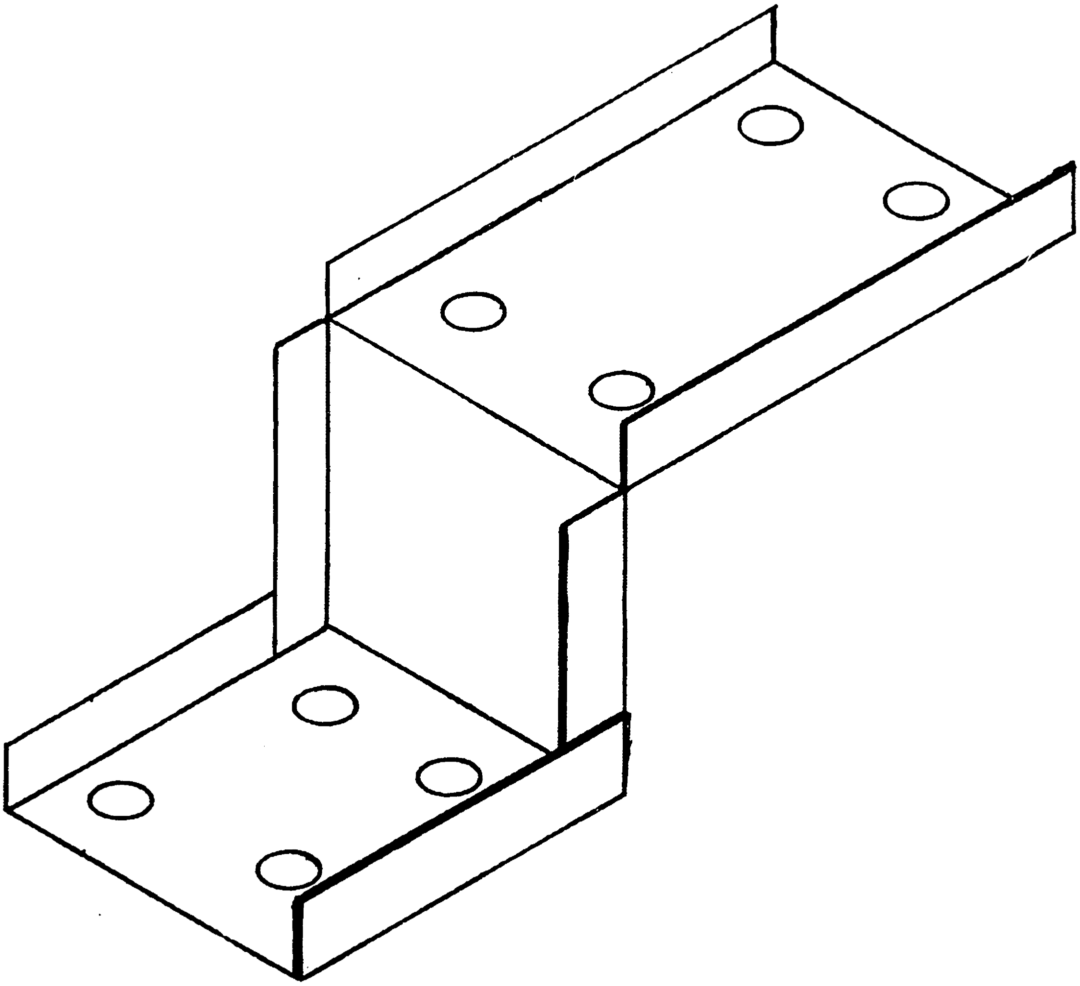


Figure 5.2: Z-coupler

of the muscles in the lower leg.

5.3. Second prototype

5.3.1. Constraints. The constraints for the second prototype were dictated by its more close approximation to an actual prosthesis and its requirement for geometric flexibility. The overall configuration required three main subassemblies: the thigh attachment, the "leg" and the skate. The thigh attachment had to be weight-bearing, comfortable, and simulate a prosthesis socket as closely as possible. It could not exactly mimic a socket since the test subjects were non-amputees and the lower leg of the subject had to be effectively removed from the system. The "leg" was required to act as a connection between the thigh attachment and the skate. Geometric adjustability was required in order to allow optimization of the variables involved. These variables were:

-wheelbase--affects turning radius for a given deck tilt angle and truck geometry

-Front/Rear "leg" position--the F/R C.G. position on the skate affects stability

-F/R "leg" angle--the F/R angle of the "leg" relative to the deck of the skate affects riding posture

-Left/Right "leg" angle--the L/R angle of the "leg" relative to the deck--when travelling in a straight line, this affects riding posture

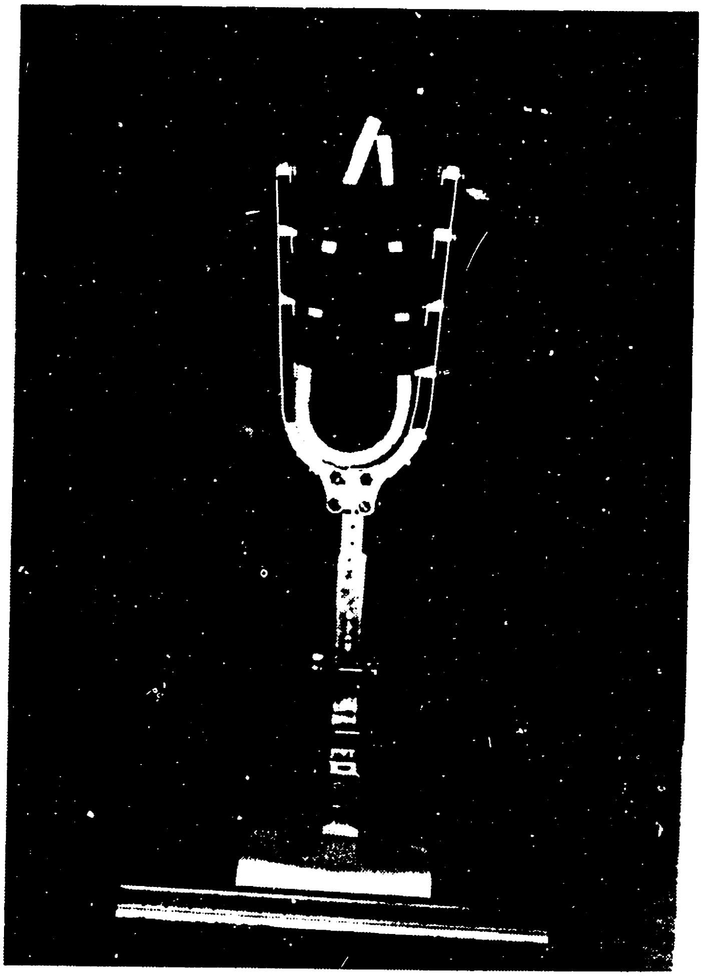
-length of "leg"--affects the height differential between the prosthesis and the pushing leg

-rotation about "leg" axis--affects riding and pushing posture.

A final constraint was that a flexible design was desired that could be easily modified for future testing of other configurations or the effect of other geometric variables (brakes, lockup, ratchets, vertical suspension, truck geometry variables, etc.).

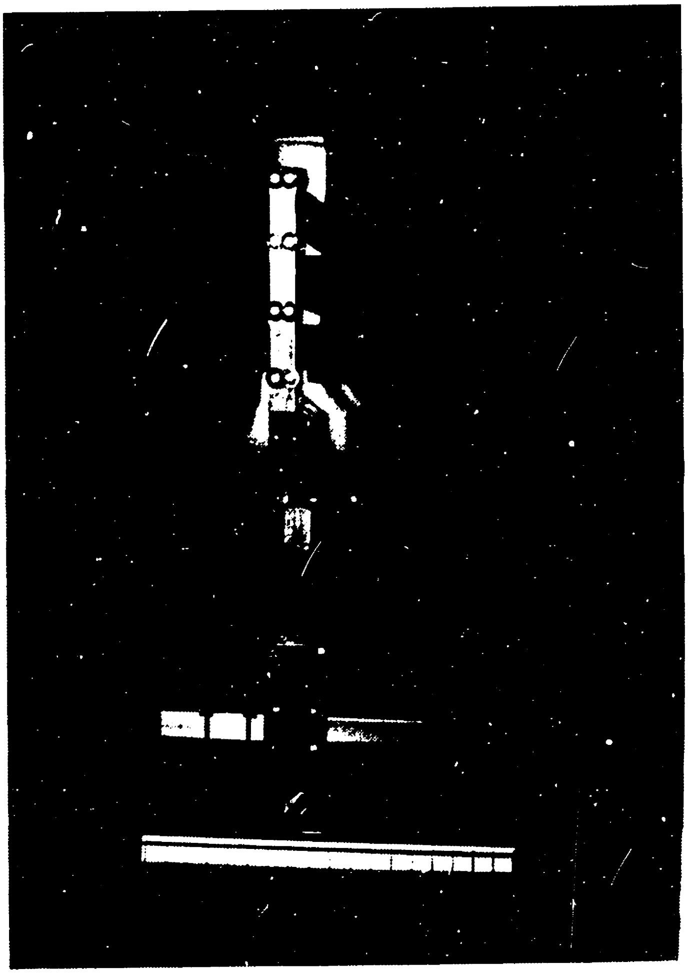
5.3.2. Design overview. The second prototype design consisted of several subassemblies. See figure 5.3. The skate subassembly was made using 1-1/2 in. square aluminum tubing as a deck. Standard skate trucks were attached using four screws that straddled the tubing and screwed into steel strips that lay across the opposite side. This produced a clamping mechanism around the outside of the tubing, allowing for wheelbase adjustment. See figure 5.4. There was enough clearance between the screws and the square tubing to allow rotation adjustment around the vertical axis. Rotating the two trucks in opposite directions caused the skate to turn to one side when ridden with the "leg" vertical. To travel in a straight line, the rider had to lean in the opposite direction. This arrangement provided a L/R "leg" angle adjustment.

The "ankle" subassembly provided the junction between



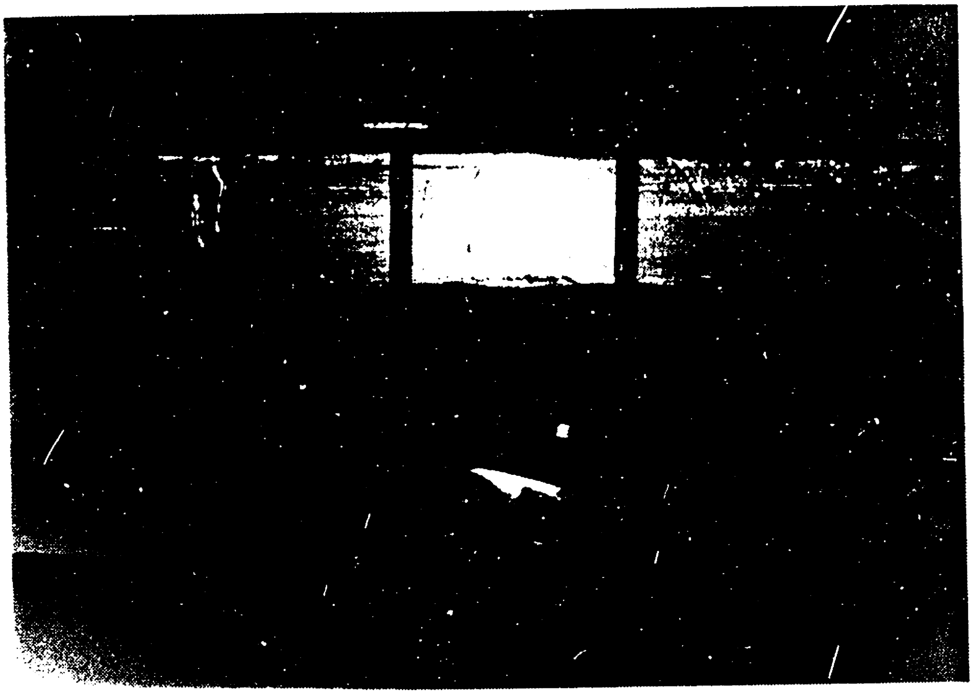
a) Front view

Figure 5.3: Second Prototype



b) Side view

Figure 5.3 cont.: Second Prototype



a) Side view

b) Perspective view

Figure 5.4: Second Prototype Truck Attachment

the "leg" and the skate and consisted of two plates which clamped to the tubing in the same way as the trucks, using four bolts. See figure 5.5. This allowed F/R "leg" position adjustment. The plates extended above the skate, and clamped the "leg" using two through bolts located at the top of the plates. Again, there was clearance between the bolts and the "leg" tubing. This allowed F/R "leg" angle adjustment. Ankle moments about the roll axis (L/R leaning) were equal to the deck moment required for turning and were therefore small. The worst moments at the ankle were those about the pitching axis (F/R leaning). The maximum would have occurred under only radical settings of the geometric variables. Using this value as a design load gave a safety margin during the more typical settings.

The "leg" subassembly had to withstand both dynamic compression loads from the rider's mass and bending loads as large as those in the ankle. The two-piece leg consisted of an aluminum bar that fit inside a piece of the 1-1/2 in. square aluminum tubing. See figure 5.6. This provided a telescoping height adjustment, and a setting was held in place by bolts. The tubing was clamped by the "ankle" and the top end of the bar was clamped by the "knee".

The "knee" subassembly provided the connection between the leg and the thigh attachment. The knee had to withstand moments of smaller magnitude than those present at the ankle and the same vertical compression loads as in the leg. The

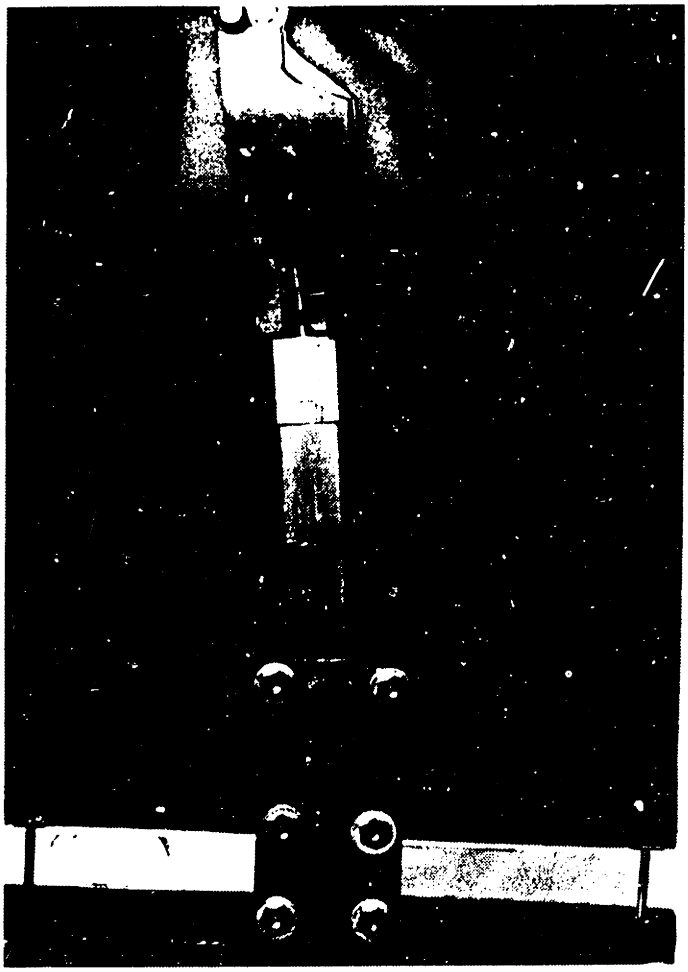


Figure 5.5: Second Prototype "Ankle"

Note Leaning of "leg"

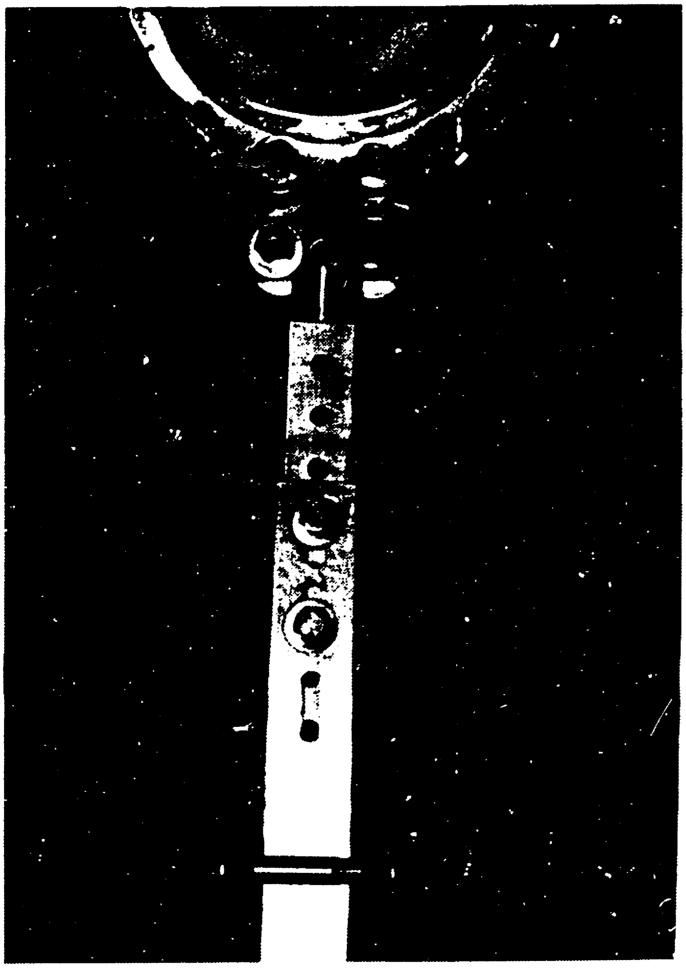


Figure 5.6: Second Prototype "Leg"

Note Telescoping Height Adjustment and

Cylindrical Section at Top for Rotation Adjustment knee was an assembly of two Y-shaped aluminum pieces. See figure 5.7. These clamped the top section of the aluminum bar which was turned down to a cylinder. This provided the rotation adjustment. The thigh attachment subassembly bolted to the upper arms of the Y's.

The thigh/knee attachment subassembly called for a comfortable, weight-bearing device. There were two design variables involved in its configuration. The first of these was whether the thigh was vertical or rotated forward. Although having the thigh forward would have allowed more of a sitting posture (weight support by buttock), keeping the thigh vertical more closely approximated the case of an A/K amputee. The other variable was the presence or absence of knee support. Although having only the thigh connected to the prosthesis would have mimicked the isolation of prosthesis control to the thigh, in an above knee stump, the end is load-bearing. Further, it was easier to maintain comfort using knee support. Thus, the configuration chosen was to keep the thigh vertical and to use knee support.

During relaxed, straight-line, level travel, the loads in the thigh attachment subassembly were limited to the dynamic vertical loads resulting from the rider's mass. During other manuevers, however, side and bending loads were introduced. The need for comfortable load bearing required the use of a well-fitted "socket" so that the load was spread over large areas of the thigh. The requirement that the

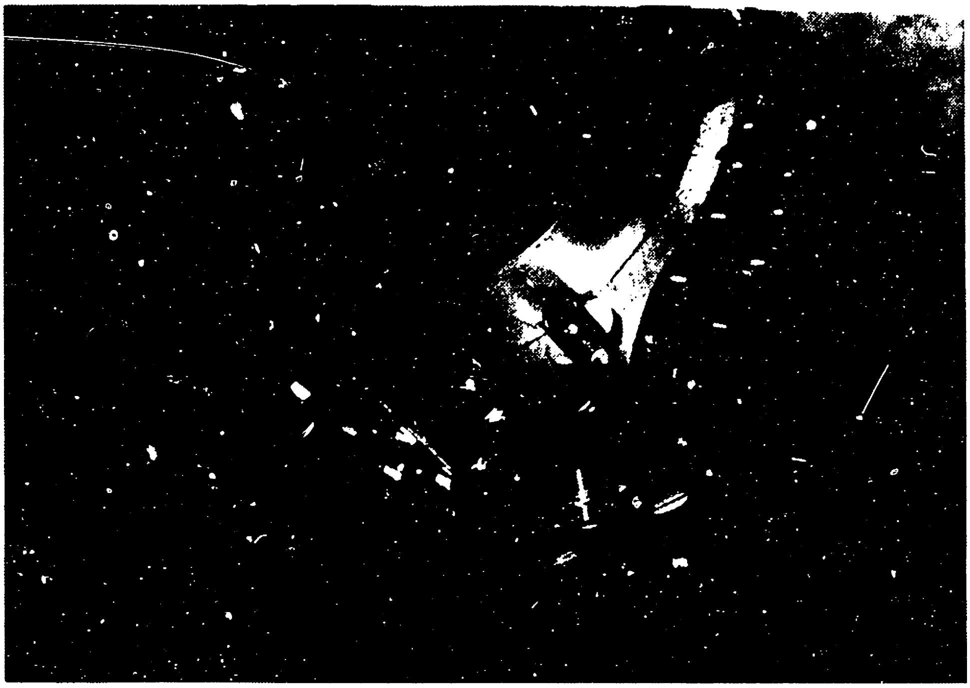


Figure 5.7: Second Prototype "Knee"

Note Cutout for Rotation Adjust

testing device be adaptable to several subjects made this a more difficult problem. The loads present precluded the use of a flexible socket. The solution arrived at involves the use of a "two-mode" beam. In the "fitting" mode, the beam was flexible and could easily be made to conform to a given shape. In the "riding" mode, the beam stored that shape in a rigid beam. The two-mode beam is a built-up I-beam constructed using two "flanges" held appart by 1/2 in. deep "web blocks". The assembly is held together by through bolts. When the bolts are loose, the flange/web block junction cannot support any shear, so the beam is only as stiff as the two flanges alone. When tightened to form an I-beam type section, the stiffness is increased substantially. The socket had a beam on each side of the thigh with wide straps around the front and rear and a layer of urethane foam padding on the inside. See figure 5.8. The fitting process involved kneeling in the socket with the beams in fitting mode and tightening the straps around the thigh (Velcro^R was used for strap connection). Bolts on the beams were then tightened to enter riding mode. See figure 5.9.

5.3.3. <u>Evaluation</u>. The second prototype was overdesigned to prevent the type of flexing present in the first prototype. Flexing of this nature would have required correction before any valid conclusions could have been

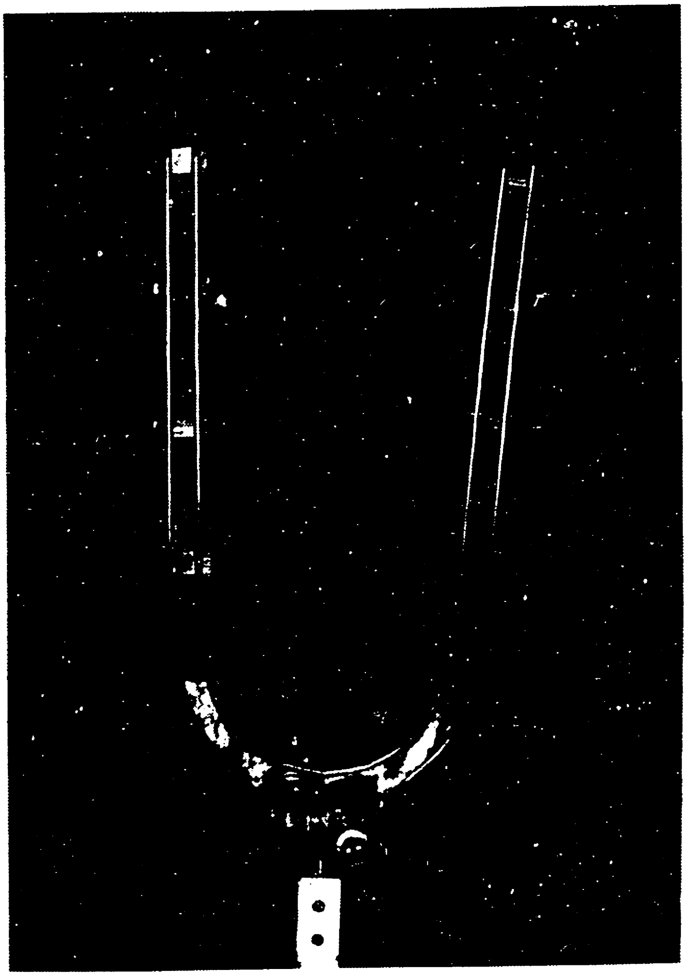
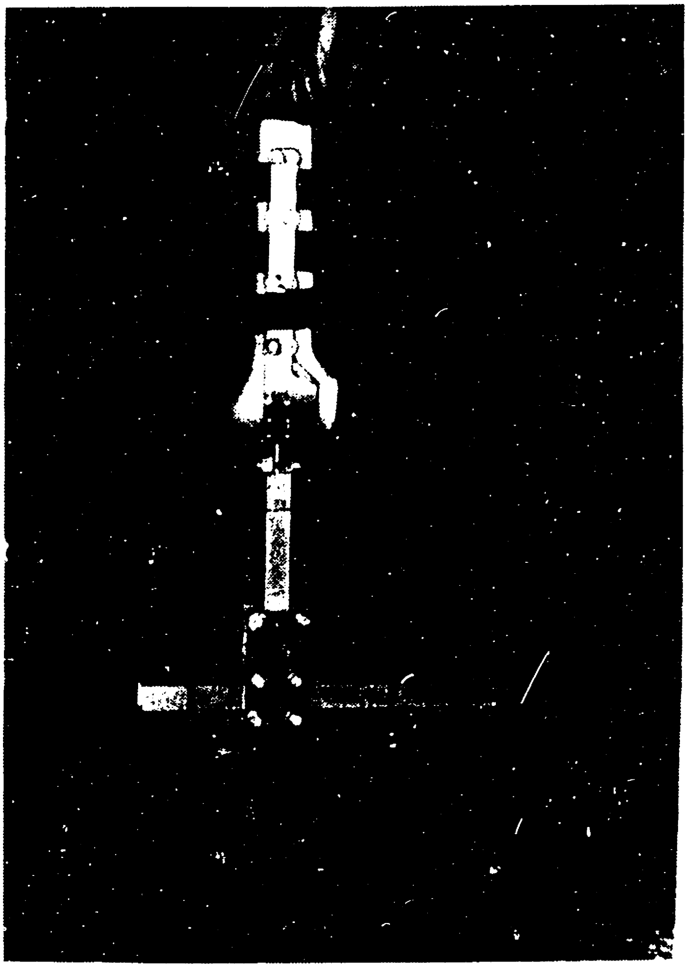
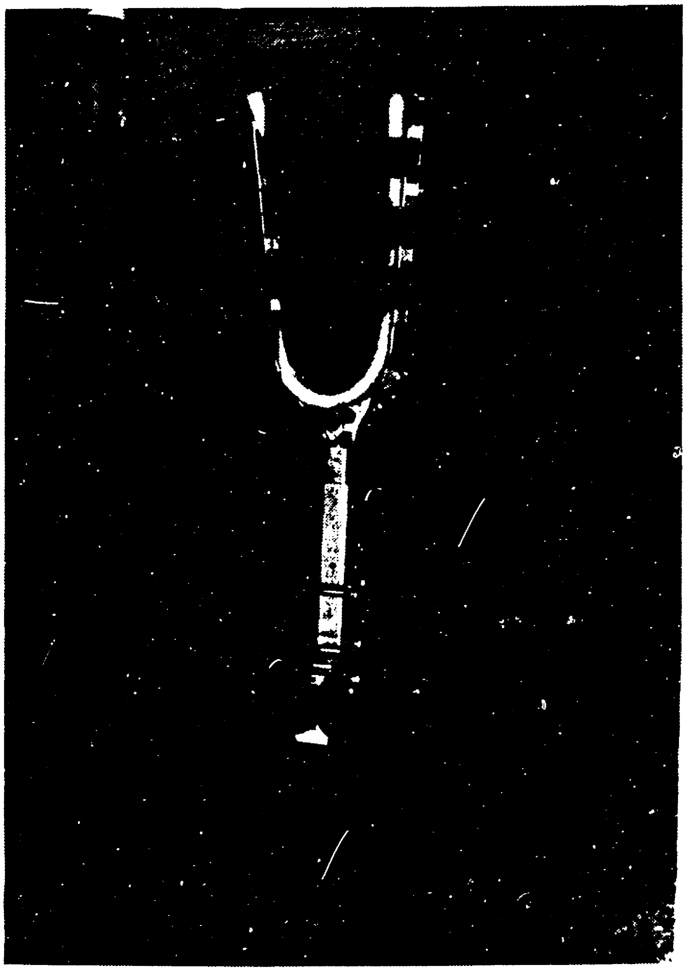


Figure 5.8: Second Prototype "Thigh Attachment"



a) Side view

Figure 5.9: Second Prototype Fitted to Subject



b) Front view

Figure 5.9 cont.: Second Prototype Fitted to Subject drawn. This produced a very rigid device and although heavy (11-1/2 lb.), it proved a satisfactory design. The ranges of geometric variables provided were large enough to cover the ranges of optimum settings. As a result, a comfortable posture was easily attainable. The adjustments were, however, somewhat involved since some of them used bolt/nut combinations requiring two wrenches for tightening. Bolt redundancy added to this problem. The ideal case would have been single bolts for each adjustment with no need to apply torque on the female threaded member. This would have limited flexibility in adding modifications, however. The design left the prototype parts unmachined for the most part, which gives it this flexibility. The padding in the thigh socket provided enough comfort to ride the prototype for periods in excess of 30 minutes. This was long enough to accomplish the required tests. Slight discomfort arose from the upper rear strap on the thigh, since the muscle here was not completely relaxed because of the lower leg's being bent back. Knee discomfort was limited to a slight sensitization of the load bearing area. When the prototype was removed from the subject's thigh, it required several minutes to stretch the leg muscles and feel normal again, but this was not serious and did not persist. The isolation of control to the subject's thigh seemed to have been accomplished, so that the use of the device by non-amputees could be accepted as a reasonable approximation to the case of an actual A/K amputee using a wheeled prosthesis.

6. Experimental Procedure

6.1. Overview

The testing procedures in this study involved riding tests of the wheeled prosthesis to determine its feasibility as a safe, effective, and controllable mobility aid. Since the purpose of the wheeled prosthesis is to provide unencumbered mobility assistance, the prototypes had to be proven over extended distances on natural terrain, without auxiliary safety devices. For this reason, the safety harness was used whenever any new terrain situations were attempted, but could then be taken off when the subject had attained enough skill. There were also gloves, pads and a helmet available for use when not using the harness.

The devices were first tested by the author (primary subject), a 24 year old male with five years of skateboarding experience. This entailed merely riding the prototypes to get a feel for their handling qualities relative to skateboards and to make any adjustments that were necessary. The prototypes were then tested by the research supervisor (secondary subject), a 41 year old male with no skateboarding experience. The testing done with this subject was much more formal in nature than with the author, and provided the bulk of the information used to draw conclusions about whether an A/K amputee with no skateboarding experience could effectively adapt to a wheeled prosthesis of this type. To provide a reference for drawing these conclusions in regards to an A/K amputee with average skills, he was asked several questions about his experience and skill levels in various activities. These activities were chosen since they require the same skills used in skateboarding. He was also asked to estimate his physical ability level in the areas of balance, reaction time, coordination and learning speed.

6.2. First prototype

A check of the performance of the first prototype was done by the primary subject. At first, only the ski boot skate was fitted, then the splint was added. The secondary subject was then fitted to the ski boot skate alone for a short time for familiarization. The safety harness was used, and techniques of upper body steering were practiced. Upon adding the splint to the system, the formal testing began. The subject made a number of passes over the 30 ft. long test area until each terrain feature presented had been mastered. This meant that the subject had attained enough skill to justify further tries at the terrain feature without the safety harness. The time elapsed while learning each terrain feature and the number of passes required were recorded. Terrain features that an A/K amputee using a wheeled prosthesis might encounter were simulated in the laboratory. The subject was told to make passes continuously at approximately walking speed until he felt comfortable with the terrain feature. The first terrain feature presented was straight, level travel over a smooth surface. Next, turns were introduced in the form of slaloms, starting with a gentle slalom that had a L/R turn cycle length of the full 30 ft. Next was a slalom with a cycle length of 20 ft. A thin throw rug was then introduced into the travel path to simulate the class of obstacles that involve an increase of rolling resistance due to soft terrain. Following this, sand was scattered on the surface and the subject was instructed to attempt turns through it to get a feel for the loss of traction that it causes. Three stages of pebbles were then scattered on the surface, increasing in size each time (these were obtained using graduated sifting screens and had nominal dimensions of 3/16 in., 3/8 in. and 1/2 in.). Barriers of various heights (up to approximately 3/8 in.) were then introduced. These obstacles are considered small (they can be rolled over) relative to a wheel radius of 1-1/8 in. The subject was instructed to force the skate to roll over the obstacles while leaning back slightly to prevent forward pitching.

When the test subject felt comfortable with all the terrain features presented, the safety harness was removed. The subject then made an attempt at climbing stairs to check performance of the wheeled prosthesis during this mode. The final test was an extended trip (approximately 300 yd.) through interior corridors to check an actual terrain situation. The primary subject kept pace on foot, to spot the secondary subject in the case of a fall and to allow a comparison of the apparent energy costs of the two modes (normal walking and using a wheeled prosthesis). Obstacles encountered were rounded bumps (1/2 in. tall) and expansion joints (3/8 in. tall by 8 in. long) with beveled edges but rough surfaces. Subject comments were noted throughout the testing session.

6.3. Second prototype

The performance of the second prototype was checked first by the primary subject. The device was fitted and after practicing in a large room the subject felt confident enough to test the device over extended distances outdoors. The terrain features encountered include sidewalk cracks, curbs, stairs, sand, pebbles, soft asphalt and ramps. The secondary subject was then fitted to the device and allowed to practice. The same extended trip as with the first prototype was then taken. The primary subject again kept pace on foot for safety and apparent energy cost comparison. After this, the subject rode the device again for a time, practicing turning maneuvers. Subject comments were noted.

7. Results and Discussion

7.1. Adaptability

Table I lists the answers given by the subject to the questions asked about his experience in various activities. The activities listed in the first column all have to do with using a single person vehicle that involves balance and weight transfer as part of its control. The second column lists the estimated time that the subject has participated in each activity. The third column lists the subject's estimate of the skill level attained in each activity. The terms beginner (learning basic skills), intermediate (basic skills mastered, learning advanced skills) and advanced (refining advanced skills) were used as a scale. The activities that are the most similar to skateboarding are surfing and slalom waterskiing since they involve standing on a single "vehicle" with a rotated posture, one leg leading the other. Windsurfing deviates from this because of the added complexity of managing a sail. Roller skating, ice skating, snow skiing and parallel waterskiing deviate in that they involve the use of a vehicle on each foot and a forward facing posture. Bicycling and unicycle riding are farther removed, but were included since they involve balance and coordination.

The secondary subject was also asked to rate himself

Table I. Secondary subject activity experience and skill

Activity	Experience	Skill level
Skateboarding	10 minutes	Beginner
Surfing	none	--
Windsurfing	n.a.	Intermediate
Waterskiing, slalom	10 hours	Beginner
Waterskiing, parallel	30 hours	Intermediate
Roller skating	20 hours*	Intermediate
Snow skiing	n.a.	Intermediate
Ice skating	4 hours	Beginner
Bicycling	n.a.	Intermediate
Unicycling	n.a.	Intermediate

n.a. = no answer

* 30 years previous to testing session

in terms of various general skills. The subject rated himself as average in balance and reaction time. He indicated that he was slightly below average in coordination/body awareness, but that a slightly above average learning speed for body motion activities tended to make up for it. He added the comment that he is usually willing to accept risks in order to participate in these types of activities. A fair assessment of the subject would be that he is about average in terms of physical ability, but that his attitude and interests have resulted in his being somewhat active in these related sports. These seem to be the characteristics that one would expect to see in an A/K amputee who expresses interest in the use of a wheeled prosthesis. In this regard, the secondary subject's performance should provide a valid indication of the feasibility of the concept.

7.2. First prototype

The primary subject found the first prototype to be a stable and controllable device. Although there was a height differential between the two sides, it was less than that of a skateboard, and did not feel overly uncomfortable. The low slung skate added a measure of stability during hard turns and sliding relative to a skateboard. Ground contact caused by flexing of the front Z-coupler limited maneuvers of this type. The subject felt that the wheelbase was too long for effective low speed maneuvering, but found that lifting the skate to change direction ("stem christies"--an option not available with a skateboard) was effective.

The secondary subject performed the tests of the first prototype during a single test session. Previous to this, he had tried the ski boot skate alone for not more than five minutes in a short corridor. During the test session, he mastered each of the terrain features in 5-10 passes and within 1-2 minutes. The total learning time required before the subject was capable of travelling over an extended distance was less than one hour. He compared this to the eight hours of practice required to be able to ride a unicycle only a short distance. The secondary subject felt uncomfortable with the height differential of the two sides and believed that he could have learned faster had there been zero height differential. The secondary subject preferred the method of stepping over small obstacles to that of rolling over them. The primary subject preferred to roll over small obstacles since this is the method he usually used in skateboard riding. Stepping down with the pushing foot to unweight the skateboard causes vertical motions of the C.G. and a larger disturbance to the coasting momentum than does rolling over the obstacle. With zero height differential between the two sides, however, putting the pushing foot down at speed was natural and efficient. When the secondary subject used the method of lifting the skate of obstacles, the failure mode was usually in catching the back wheels on the obstacle. This was attributed to the height differential. The subject was able to climb stairs with the prototype and naturally picked the expected side-stepping mode. During the extended trip, the secondary subject easily kept a controllable pace that required the primary subject to jog alongside. At the end of the trip, the secondary subject did not display increased breathing or heart rate, while the primary subject, who jogged, displayed a significant increase in breathing and heart rates. This provided a simple approximation to the comparison of energy costs. The secondary subject commented that his conception of a distance travelled was more in terms of time than energy expended while using the device. These results are in agreement with the experience of the author.

Several different "gaits" of the wheeled prosthesis could be identified. The normal skateboard gait involves weight bearing and coasting on the wheeled side, with pushes by the other leg as needed. This was not natural for the subject, and he preferred a hybrid rolling/walking gait. This is different from the skateboard mode in that there is more weight transfer onto the pushing foot and the coasting phase is shorter. The rolling side was relied on more as speeds increased. During the extended trip, the secondary subject also developed a high speed (jogging speed) gait in which the wheeled limb would swing out to the side during the coast phase in a motion similar to that used in ice skating. While the secondary subject was learning the slalom, it was observed that as the turning became tighter, there was a point at which the subject changed from skateboard steering to the stem christie method. He was in agreement that the wheelbase was too long and low speed maneuverability would be improved with a shorter wheelbase. In terms of mimicking a wheeled prosthesis, both subjects felt that the first prototype still allowed too much use of the muscles of the lower leg.

7.3. Second prototype

The primary subject felt comfortable using the second prototype and with only several minutes of practice was able to travel over natural outdoor terrain. The removal of the lower leg from the system did not change the handling features of the prototype very much. A difference was noticed, however, in the performance of the device in rolling over small obstacles, and a more determined effort was required to accomplish it without pitching forward. Further, if the prototype was pushed to the point of wheelying (the point where the wheels at one end lift off the riding surface), it was difficult to prevent the device from rolling out from underneath. This was related to the observation that wheelies could always be initiated due to the rigid attachment to the skate at the ankle. On a skateboard, it is impossible to wheely if the feet are kept within the wheelbase. The device had a problem associated with the rigid ankle. When following a path on a slope other than the maximum qradient line, the prototype had a propensity to turn uphill. Since the leg must remain perpendicular to the surface for straight line travel (assuming a 90° L/R leg angle), the device will turn uphill if the leg is forced to remain vertical. This effect was noticed on the short, wheelchair ramps cut out from curbs, and resulted in a sudden tendency for device to pull across under the rider, creating the potential for a fall. It was not clear if practice could improve this situation. The wheelbase was adjusted to allow a tight turning radius, and this solved the low speed maneuverability problem present in the first prototype. A low speed U-turn was able to be accomplished in a space less than five feet wide. Several hard turns and sliding were tried and the performance of the device was similar to a skateboard. An advantage of the prototype over skateboards was that the rigid connection with the skate allowed these maneuvers without the need for both feet on the skate. The pushing foot could therefore be used as a type of outrigger.

The secondary subject found the second prototype to be easier to ride, due to the lack of height differential between the two sides. This was the case even with the lower leg removed from the system. He was able to immediately ride the device and after a short practice the extended trip was taken. The results were similar to the first extended trip. He was able to maintain a speed slightly faster than walking with no noticeable increase in breathing or heart rate. The preferred gait was still the roll-walking mode, yet he was able to coast and do gentle turning when asked. The secondary subject lost balance several times but was able to catch himself with his other foot. Both subjects felt a little insecure about leaning away from the pushing foot since it is harder to catch a fall on this side using the pushing foot.

8. Conclusions and Recommendations

It is the conclusion of this study that the concept of using wheels to improve the mobility of A/K amputees is certainly feasible. Further, it has been shown that using skateboard steering provides effective and safe control over the majority of terrain situations. The energy cost of rolling mode travel appears to be significantly less than that of normal walking. Small obstacles presented little problem, and stepping over larger obstacles was easy. The worst case of energy cost in using this device would be in non-rolling mode travel, but this should be no worse than the energy cost of using conventional prostheses. The risk involved in using a wheeled prosthesis, though increased over normal walking, is still at an acceptable level. The issue of cosmetics is still a problem, since nothing can be done about the appearance of the rolling mode gait. However, the leg/foot appearance and the non-rolling mode gait appearance should both approach the levels of cosmetics provided by conventional designs.

Recommendations for further research include the testing of other configurations such as the scooter cane or a device that the rider sits on. Also, other steering systems and the use of a single track device with no steering should be tried. Since skate steering appears to be promising, attention should be given to solving the problems associated with the rigid ankle of the prototype, and to optimizing the geometry for this application. Also, a study of the energy costs of this locomotion mode should be done to provide more exact data than obtained in this study. Finally, the auxiliary devices mentioned such as brakes/lockup, ratchets and vertical suspensions should be investigated further to assess their applicability.