DESIGN AND STUDY OF A PROTOTYPE ABOVE KNEE PROSTHESIS WITH WHEELS

by

Janet Laddie Zahradnik

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE
DEGREE OF

BACHELOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1987

Signature of
Author____________________________________

Department of Mechanical Engineering
May 8, 1987

Certified
by______________________________

Woodie C. Flowers
Thesis Supervisor

Accepted
by__________

Peter Griffith
Chairman, Department Committee

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Submitted to the Department of Mechanical Engineering
on May 8, 1987 in partial fulfillment of the
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Abstract

A study was carried out to compare two wheel configurations for an above-knee prosthesis. Three prototypes were built and tested each with a tandem wheel configuration. All the prototypes were built for use by normal non-amputee individuals. The final of these prototypes was tested in comparison to a prototype with a skateboard wheel system built in a previous study. These prototypes were compared on the basis of safety, control and mobility.

The stability and control of the wheel configurations varied with each test subject. The study indicated that personal preference and athletic experience dictated the stability of the subject on each prototype. The stability in turn directly affected the ability of the subject to control and maneuver each prototype.

This study concludes that the stability of the prototype is a major constraint. However, the preference of wheel configurations varied for each subject, thus an optimal wheel configuration can not be generally defined. Recommendations for further research were made.

Thesis Supervisor: Woodie C. Flowers

Title: Associate Professor of Mechanical Engineering

to mom and dad, naturally
(and with much love)

and
to the kids at H.R.S. who started this in the first place.

ACKNOWLEDGEMENTS

To the many people who helped and supported me through the 'trauma' of thesis I give my sincere thanks.

First in line for thanks is Prof. Woodie Flowers for introducing me to the idea and not letting me give up. He gave me alot of guidance but never once told me what to do. I am also grateful for his infinite patience and extra help while watching me try to complete this report (almost) on time.

Next, are my daring subjects Megan Smith, Mark Fenton, Krispen and once again Prof. Woodie Flowers. I'd like to thank them for the time they took away from their own work and for the tremendous help they provided as test subjects. More than that, they provided me with more encouragement and cheeriness than I thought possible as the deadline drew near. Special thanks also goes to Mark for keeping down the panic and steadying the coffee more than once.

More thanks also goes to Robert Samuel and Norman for their patience and advice in the building and misbuilding of the prototypes. They provided me with volumes of practical advice that won't soon be forgotten. Henry Houh and Phyllis Kristal also deserves my gratitude for taking time out during the busiest time of year to make sure I had pictures.

I would also like to thank my roommate, Maria Kozloski, and my friends at Baker for putting up with me and standing by me while I produced this report.

My warmest thanks go to Michael Foley who had to put up with the worst. He never stopped giving.

Finally, I would like to thank my parents for their support not only this term, but throughout my first four years at MIT. They put up with many phonecalls from a hysterical daughter, always managed to calm me down and never once lost faith. I would have never made it this far without their warmest love and support, something which I know will always follow me.

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1. INTRODUCTION

Walking, though a simple act for most people, is not a trivial issue for unilateral above-knee (A/K) amputees. Even when fitted with state of the art prostheses, walking is a difficult and uncomfortable task. Twice as much energy is required to manipulate a prosthetic leg than is required for ordinary walking. Locomotion thus becomes a highly restricting factor for an amputee. Conventional prostheses are poor substitutes for legs. They do not have the control, elasticity, flexibility or degrees of freedom supplied by human limbs.

Other options available to amputees are wheelchairs and crutches. These also have their limitations in mobility as well as accessability. An ideal solution would be a mode of locomotion comparable to walking but requiring less energy and providing greater mobility than present prostheses. A radical proposal to solve these problems is a prosthesis design with wheels. Theoretically, this type of prosthesis would provide greater mobility and require less energy expenditure. This increase in mobility is exemplified in conventional skateboarding and rollerskating.

Clearly a prosthesis with wheels creates problems different than those of skateboarding and rollerskating or those of conventional prostheses. One such problem is the lack of the knee and ankle joints for control. However, if the design of a wheeled prosthetic device is executed correctly, it could prove tremendously beneficial for increasing the mobility of an amputee.

A study of the feasibility of this approach was conducted by Michael J. Kohlbrenner in 1985. He tested a skateboard wheel configuration which employed a lean-steering system. His results were very positive and suggested that further study was warranted. His study demonstrated that the skatebaord wheels, though controlled without the use of ankle and knee joints, were safe, controllable and provided a large amount of mobility at a low apparent energy cost.

These encouraging results were also supported by Tom Andrew, a prosthetist and above-knee amputee. Andrew built a wheeled prosthesis utilizing a skateboard wheel configuration. He felt that continued study of the wheeled prosthesis would be beneficial.

This study examines another wheel geometry with the aim of optimizing the wheel configuration. A tandem wheel geometry was chosen for a number of reasons. First, it has been demonstrated to be a generally successful means of locomotion with a high degree of maneuverablity through the use of Roller Blades. The fact that the tandem wheels can be bought already made in this configuration was also useful. A single track wheel arrangement does not have a steering mechanism (unlike the skateboard system) but is controllable by a pivoting action. Since this is a dissimilar action to the lean steering of the original prototype it is worth studying in comparison. This will help to define actions and degrees of control available to the amputee. A final reason for choosing the tandem geometry was potential for aesthetic applications. Cosmesis, for a prosthesis, is an important issue. A final design of a wheeled prosthesis would have to be aesthetically pleasing - resembling a human leg as closely as possible - to be practically useful.

In comparing the tandem wheel design to the skateboard geometry, it will be possible to learn more about the dynamics of riding a wheeled prosthesis. Each of the wheel configuration introduces a variety of steering and balancing issues which are not ordinarily addressed under the conditions imposed by an A/K prosthesis. By incorporating the positive aspects of each of the configurations, an optimal design could be acheived.

2. DESIGN APPROACH

2.1 CRITERIA

There are certain limiting issues that should be addressed in designing a wheeled A/K prosthesis. These criteria provide a basis for assessment and lead to an iadealized set of goals and constrains for the prosthesis.

2.1.1 Safety. Above all, the wheeled prosthesis must be safe for the user as well as for other people around. An unsafe device is useless to the amputee. Safety especially becomes and issue in dealing with an unfamiliar apparatus containing free rolling memebers - wheels. Rollerskating and skateboarding are in general more dangerous than normal walking. Using a wheeled device for mobility, without the use of the knee and ankle joints for control, may present a problem. Assessment of the safety of any new wheeled mobility device deserves close attention.

Safety can be judged by dividing it into several factors such as stability and control. The control of 'walking' with the wheeled prosthesis should be comparable to the that acheived with a conventional prosthesis. Stability and balance are issues of comfort as well as safety. An amputee would have to fight for balance if using an unstable device. This could cause fatigue and general discomfort as well as jeopradizing safety.

2.1.2 Mobility. Mobility is the specific variable which is potentially optimized by the concept of a wheeled prosthesis. It can be judged on the basis of speed, distance, energy consumption, agility, versatility and executable terrain. Thus, mobility is defined as the ability to move over a given terrain and negotiate obstacles. The potential increase in mobility of a rolling mode of locomotion as a function of speed, distance and energy is demonstrated by conventional skating, skateboarding and even bicycling.

How fast and far a person travels are closely related to energy expenditure (they are also related to stability but that is an issue more clearly discussed in the safety category). If a method of locomotion requires a considerable amount of physical (and mental) effort, a limited amount of endurance will greatly restrict the speed and distance traveled. Wheels, in general, are expected to require less energy then walking. This is due in part to an 'energyless' coast period which is propelled by energy stored in momentum.

A wheeled prosthesis controlled without the ankle or knee joints is controlled by the upper body. If there is exessive extraneous motion required to put the wheels in motion, to balance or to control the device, a large amount of energy may be expended. This type of less apparent energy sink should not be overlooked when assessing the apparatus.

Agility and maneuverability are also closely related to mobility. Without reasonable control, the prosthesis is limited to travel in areas essentially without obstacles. A wheeled prosthesis should have at least as much maneuverability as conventional prostheses. The possibilty of increasing agility - quickness and ease of movement - is a way a wheeled prosthesis could gain on mobility.

Terrain is another potentially restricting feature. Ideally a prosthesis should not be limited to specific terrain features. A prosthesis with wheels, however, has a few apparant limitations. Some such limitations are a large amount of sand or stairs. To facilitate this, a final prosthesis design would undoubtedly include a 'walking' mode. This would require the locking of the wheels and the unlocking of the knee. A swing knee does not appear to be a feasible option during rolling mode since it would impair control of the device. It is, however, normally a part of conventional prosthesis.

Even with the walking option, a wheeled prosthesis has to be able to travel over a reasonable variety of terrain conditions. This characteristic is dependent most directly on the wheels of the prosthesis. Wheels with large radii can handle larger bumps and obstacles. Height of the wheels in relation to each other, the addition of a vertical suspension system or a shock absorption system also would increase the ability to handle bumps. The performance of wheels in different terrains features as well as the compatibility of a configuration to these and other mechanical features (such as wheel lock and brakes) should be noted.

2.1.3 Aesthetics. The cosmetics of a prosthesis is not to be an underestimated criteria. Reasonable similarity to able-bodied persons is important, not only in the act of walking, but also in the aesthetics of the device itself. Obviously, a rolling motion is dissimilar to a normal walking gait. An amputee may, however, be willing to sacrifice some cosmetics in order to acheive a considerable increase in mobility. It would be desirable to at least design a wheel configuration that is compatible to a prosthesis design close in appearance to the human leg.

This could be accomplished in several ways. The most obvious and convenient is concealing the wheels within the 'shoe' of the prosthesis. A dual mode (rolling and walking) prosthesis would also preserve some similarity to able-bodied walking. This would require the design of retractible or lockable wheels. The amputee could then choose a method of locomotion depending on his specific needs and desires. As mentioned earlier, an amputee may also prefer a 'walking' mode over a 'rolling' mode in some instances for reasons other than cosmesis.

2.2 DESIGN CONSTRAINTS

The prototypes built for this study were designed for non-amputee subjects. To adequately test the described issues the prototypes had to imitate an actual A/K prosthesis. The knee and ankle joints were therefore immobilized. A perfect simulation of these conditions is difficult if not impossible. It is, however, critical that they do so closely enough to provide a fair assessment of the prototype. An inadequate prototype with extraneous variables could mask the issues under evaluation.

There was a progression of prototypes, each more closely imitating an A/K prosthesis. The first was used to examine the feasibilty of a linear wheel arrangement. Prototypes following this one were used to assess the wheel configuration (singly and in comparison to the skateboard system). Several subjects tested the later prototypes to provide more conclusive information. It was therefore necessary that the prototypes were able to accomodate persons of various heights and sizes. To optimize the comfort and posture of the subjects, it was also necessary to have the flexibilty of adjustment of the geometry of the prototype.

Once an acceptable prototype with a linear wheel arrangement was built, a rigorous experiment was designed and executed to compare this geometry to
the original skateboard configuration. The two prototypes were compared on the basis of safety, control and mobility.

2.3 THE TANDEM WHEEL CONFIGURATION

The Roller Blade wheels were used in the various prototypes with their relative alignment preserved (see Figure 2.3.1). The wheels are lined up in a tandem arrangement such that only two wheels are touching the ground at a time. The actual dynamics of this arrangement was not examined in this study but the following points were noted.

The askew arrangement creates a radius allowing the use of lean-steering. This radius, however, is large and therefore limits the use of this steering method. The small area of contact with the floor permits the use of a pivoting action to steer. The raised wheels increase the size of obstacles that can be successfully navigated. Typically, a wheel can ride over an object one half the size of its diameter. In the Roller Blade arrangement the maximum object size is about one half the wheel diameter plus the distance of the wheel from the floor. This increase is considerable when the two rear wheels are in contact with the floor raising the first two wheels off the floor.

The Roller Blades also have a backstop which is useful in assessing the type and necessity of a braking mechanism. A stopper type brake could only be employed at the rear of the wheel arrangement on an actual A/K prosthesis. A/K amputees do not possess the range of motion required to actuate a front stopper.

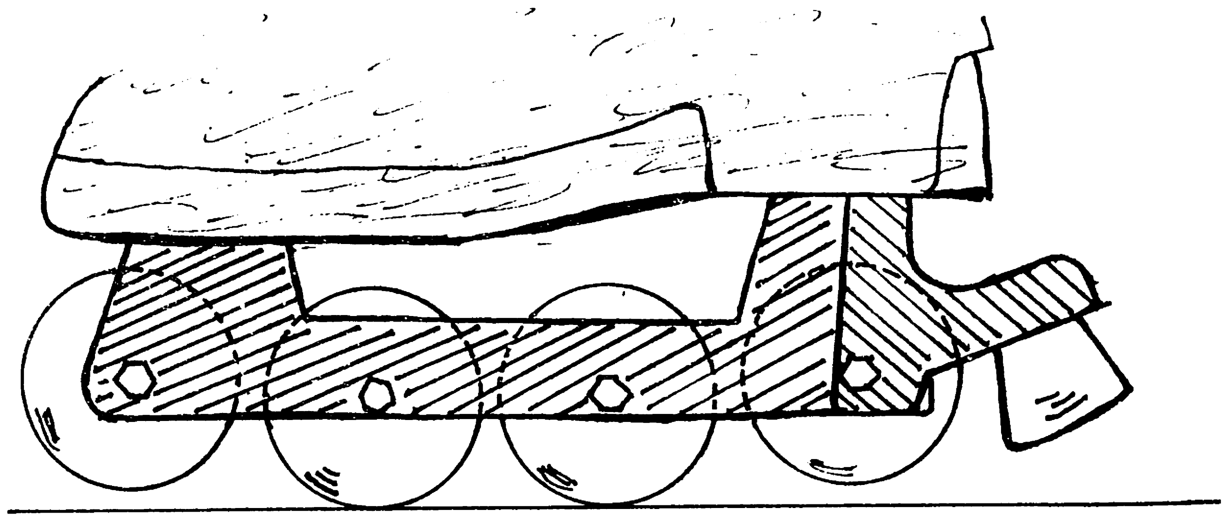


FIGURE 2.3.1 TANDEM WHEEL ARRANGEMENT
(Note wheel alignment and backstop.)

3. EXPERIMENTAL APPARATUS

3.1 SAFETY EQUIPMENT

During the testing sessions, the safety of the subjects had to be insured. Since the use of an unfamiliar riding device introduced an element of physical danger to the subjects, they were required to wear safety equipment during testing.

Each subject wore a bicycle helmet, knee and elbow pads, and used a crutch (see Figure 3.1.1). During the initial learning stages, another person walked beside the subject to help prevent a fall. As the subjects became confident and displayed proficiency in riding, the safety equipement was removed. This was done at the discretion of the researcher and the subject.

3.2 THE FIRST PROTOTYPE

The first prototype was designed and built to test the feasibility of a tandem wheel configuration. A prototype was designed to be worn by a normal individual. To simulate a prosthesis, the ankle and knee of one leg were immobilized. A Roller Blade boot was used to immobilize the ankle as well as to supply the tandem wheels. The stiffness of the knee joint was imitated by a knee immobilizer which the subject also wore. This is illustrated in Figure 3.2.1.

a) front view

b) side view

FIGURE 3.1.1 SAFETY EQUIPEMENT

a) front view

FIGURE 3.2.1 FIRST PROTOTYPE FITTED TO SUBJECT

a) side view

FIGURE 3.2.1 FIRST PROTOTYPE FITTED TO SUBJECT

This created a fairly large height difference between the subject's two legs. The difference was compensated for in two ways. First the subject simply dorsal-flexed the sound ankle extending the leg to a height comparable to the leg wearing the prototype. This eventually became tiring. The subject then wore the corresponding Roller Blade boot with its wheels immobilized on the foot of the sound leg. This also proved to be problematic since it immobilized the sound ankle.

The first prototype was not an accurate simulation of actual A/K prosthesis conditions, however, it provided a basis for further testing.

3.3 ORIGINAL PROTOTYPE

The original prototype designed by Kohlbrenner (see Figure 3.3.1) was used in this research in two ways. First, the device was tested by the principal subjects in order to compare the skateboard configuration of this prototype to a single track configuration. The prototype was also modified and used in the design of both the second and third prototypes. The critical parts of Kohlbrenner's prototype are described below. A more detailed documentation can be found in his thesis, A Feasibility Study of a Wheeled Prosthesis with Skateboard Steering for Unilateral Above Knee Amputees.

To use the prototype, a normal person places his leg in a kneeling position into a thigh attachment (see Figure 3.3.1). This attachment simulates the socket of an amputee's prosthesis. The thigh is tightly strapped into this socket to immobilize it as much as possible. Any movement in the socket will hinder the control of the prototype and therefore the safety of the subject as well as the assessment of the apparatus.

FIGURE 3.3.1 KOHLBRENNER (ORIGINAL) PROTOTYPE FITTED TO SUBJECT
(perspective view)

The socket attaches to a "leg" section via a two dimensional "knee" joint which allows rotational adjustment between the thigh and leg sections (see Figure 3.3.2). The plane of rotation is perpendicular to the "leg". This "leg" imitates the shank section of a conventional A/K prosthesis. It has a telescoping height adjustment. Maladjustment of height would result in the misalignment of the hips in the transverse plane. This would cause extraneous motion of the upper body in compensation.

The "leg" of Kohlbrenner's prototype attaches to a skateboard wheel configuration. This "ankle" joint allows for considerable adjustment of the center of mass over the wheels. The distance of the skateboard trucks relative to each other can also be varied. These adjustments are all useful in optimizing the wheel and prototype geometries.

3.4 SECOND PROTOTYPE

The results of testing the first prototype indicated the potential of the tandem wheel configuration. To more accurately imitate an A/K prosthesis a second prototype was built.

The Roller Blade with the single track wheel arrangement was attached to the thigh and leg sections of the original prototype (see Figure 3.4.1). This allowed the use of the rotational and height adjustments of the original prototype.

A Solid Ankle Constant Heel (SACH) foot was placed into the Roller Blade boot and attached to the lower portion of the leg. The ankle joint was immobilized with a wood and aluminum brace to prevent lateral movement (see Figure 3.4.2). Motion in the sagital plane, particularly in the anterior direction, was prevented by a turn-buckle assembly (see

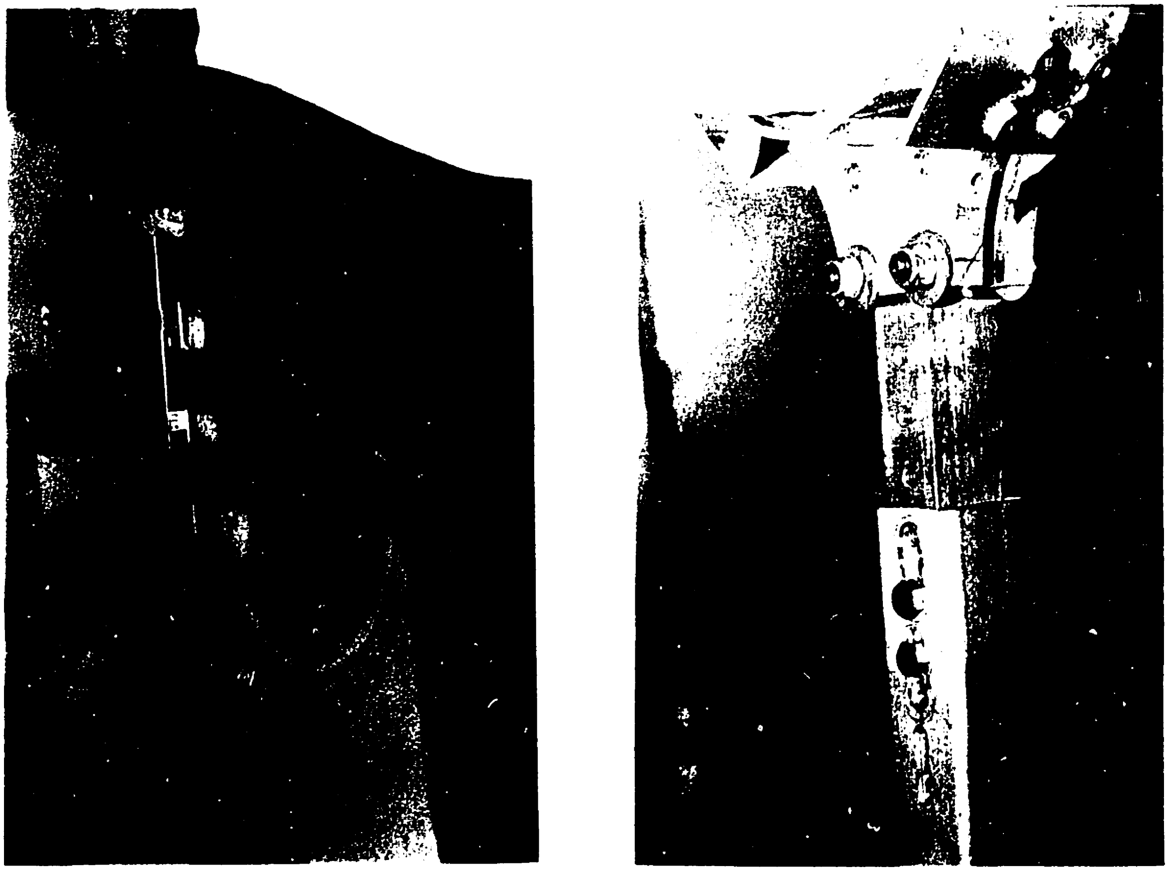
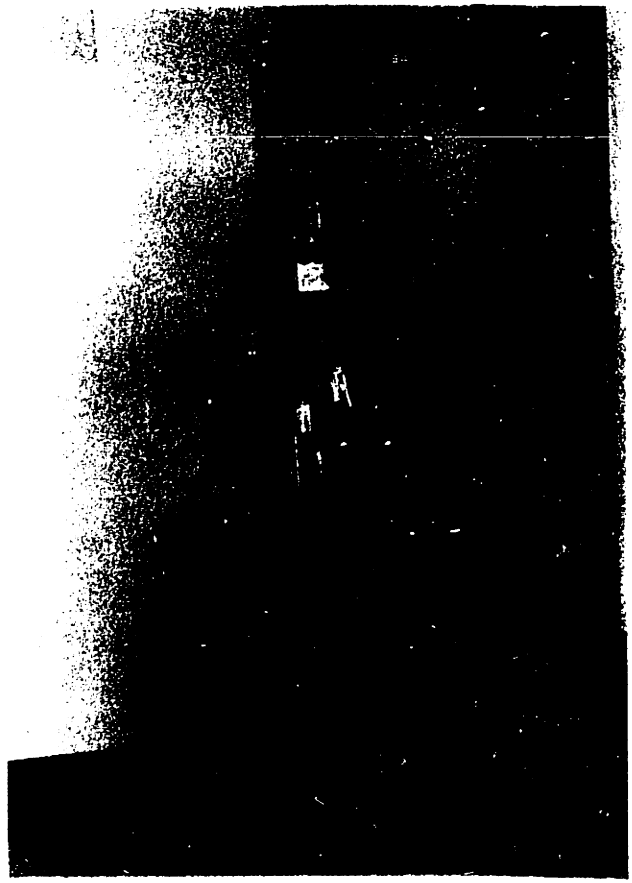


FIGURE 3.3.2 THIGH AND LEG SECTIONS OF ORIGINAL PROTOTYPE
(Note rotational adjustment of the 'knee' joint and telescoping height adjustment of the 'leg')

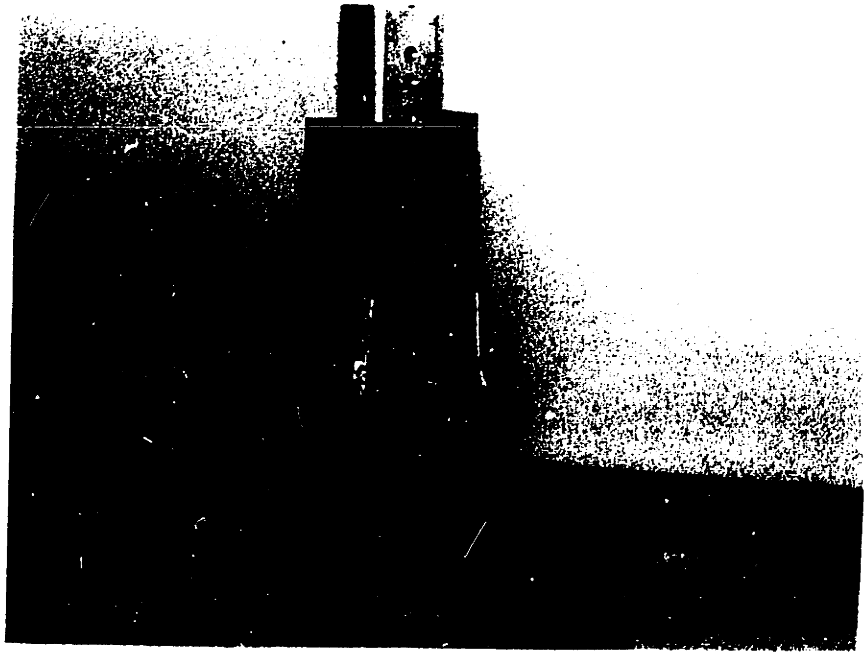
a) front view

FIGURE 3.4.1 SECOND PROTOTYPE

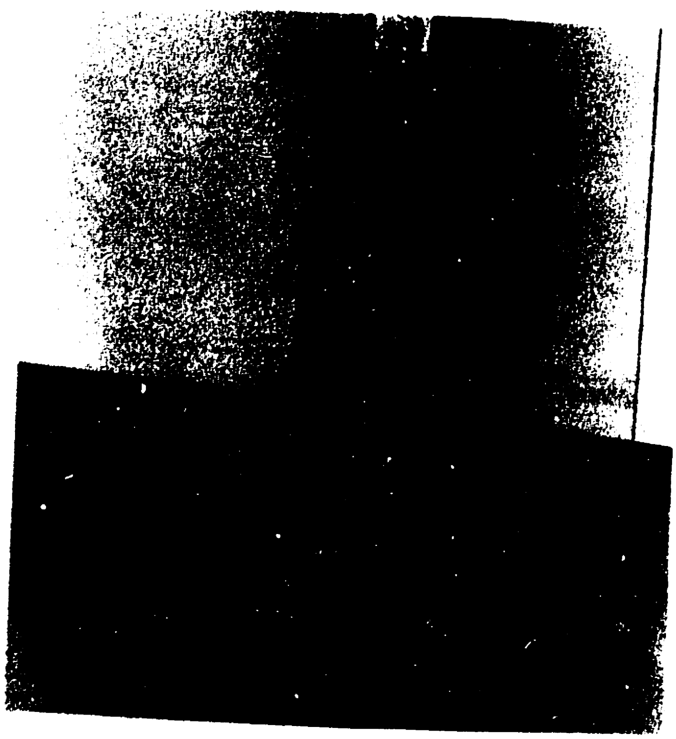


b) side view

FIGURE 3.4.1 SECOND PROTOTYPE
(Note alignment of wheels and prototype leg.)



a) Ankle 'brace'.



b) Ankle 'brace' fitted into Roller Blade boot.

<u>FIGURE 3.4.2</u> SECOND PROTOTYPE LATERAL ANKLE IMMOBILIZATION

FIGURE 3.4.3 SECOND PROTOTYPE ANTERIOR ANKLE IMMOBILIZATION

Figure 3.4.3). This was attached to the back of the boot and the thigh attachment and was adjustable to height.

The second prototype provided reasonable rigidity in the ankle in the lateral direction. In the longitudinal direction, however, the ankle was not as stiff. The second prototype did not allow adjustment of the position of the center of mass over the wheels. This was very restricting. In the longitudinal direction, the center of mass was located between the back two wheels (see Figure 3.4.1b).

The design of the Roller Blade boot also created another alignment problem. The boot caused the leg of the prototype to lean in the medial direction. This seemed to cause instability. This lean was therefore partially corrected by modifications in the boot (see Figure 3.4.4). This alignment was also tested.

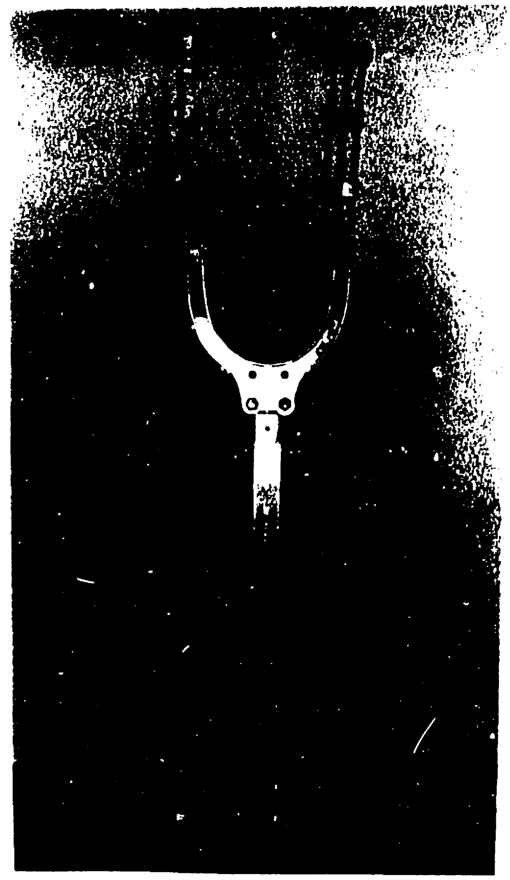
A non-optimal alignment of the center of mass or flecxibility of the "joints" could potentially mask the results in testing and detract from an acccurate assessment of the wheel configutation.

3.5 THIRD PROTOTYPE

This prototype was designed in an attempt to alleviate some of the problems observed in the second prototype (particularly the inflexibility of adjustment). This would provide a better means for creating an optimal alignment geometry and a more accurate assessment of the linear wheel arrangement. The third prototype is also very similar to Kohlebrenner's design and therefore provided a good basis for comparison of the two wheel configurations (see Figure 3.5.1)

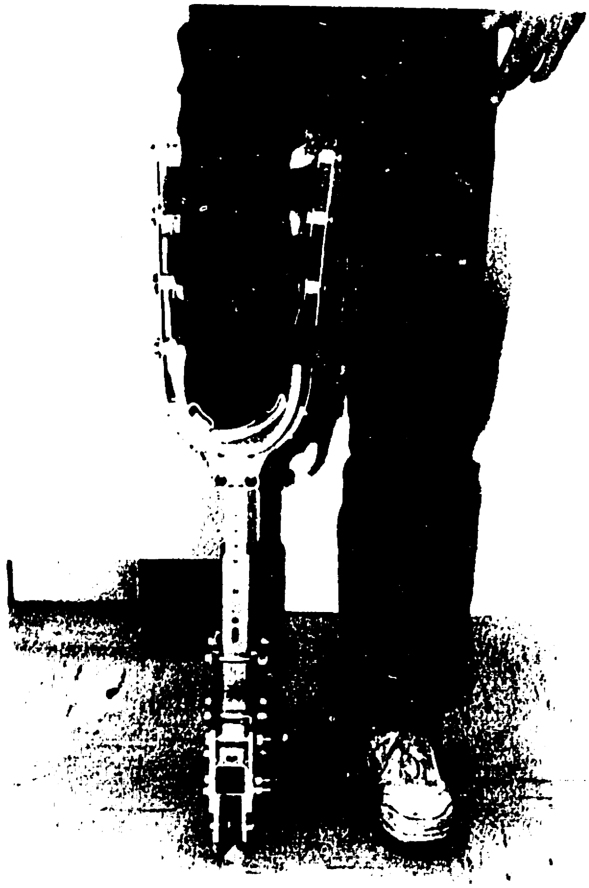
The wheels were removed from the Roller Blade and arranged

a) original lean



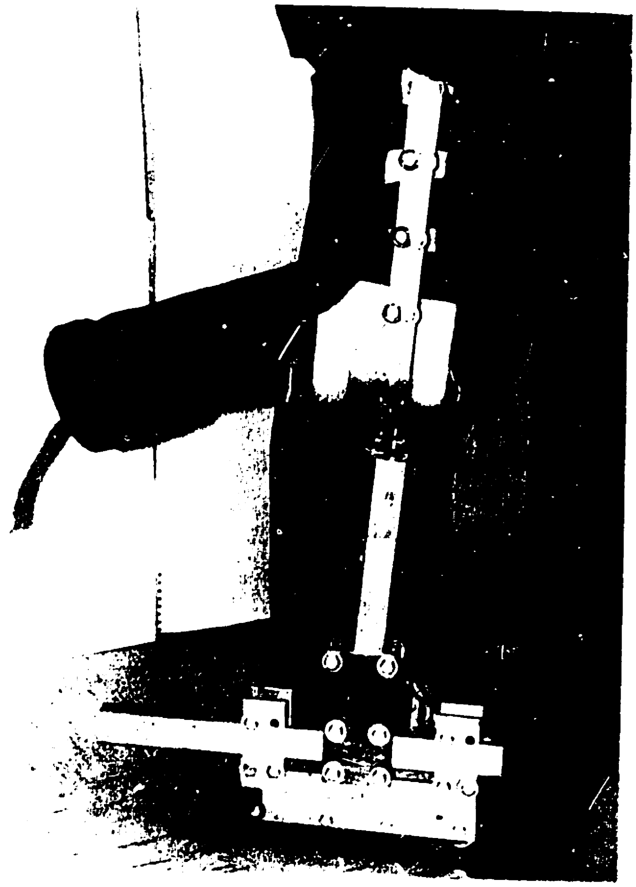
b) corrected lean

FIGURE 3.4.4 LEAN OF 'LEG' SECTION OF SECOND PROTOTYPE



a) front view
(Note alignment of wheels and 'leg' section)

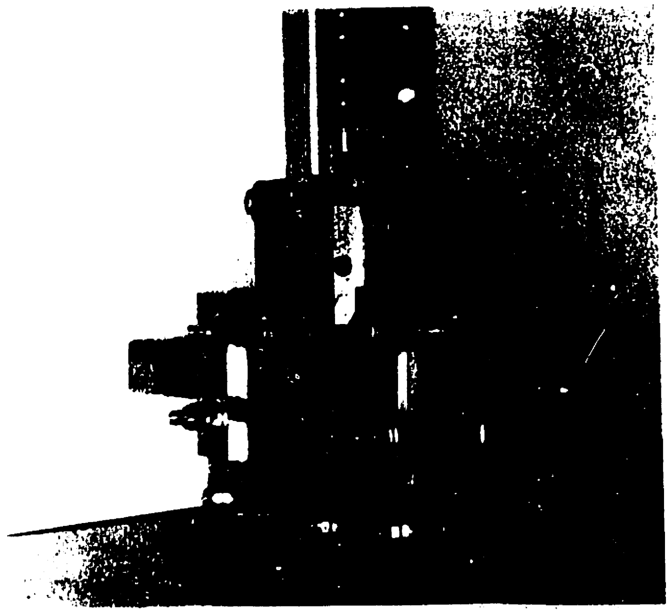
FIGURE 3.2.1 THIRD PROTOTYPE FITTED TO SUBJECT



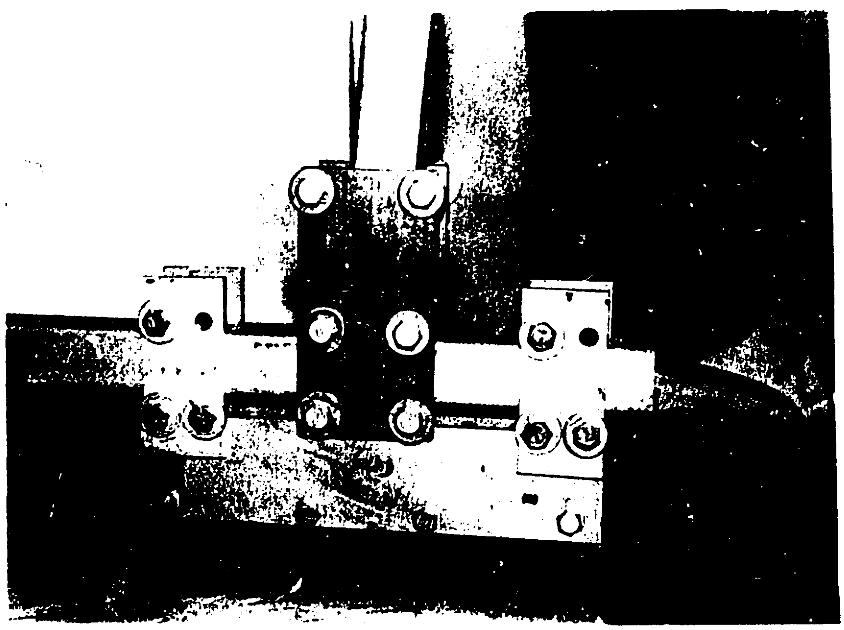
b) side view

FIGURE 3.5.1 THIRD PROTOTYPE FITTED TO SUBJECT between two plates in the same relative positions such that only two wheels at a time are in contact with the floor (see Figure 3.5.2). This wheel bracket is attached to the base of the original prototype.

The third design provided complete rigidity as well as adjustment of the ankle angle (the angle between the leg and wheel base) in the anterior/posterior plane. This angle affected the posture and balance of the subjects. The leg was aligned directly above the wheels in the lateral direction and allowed adjustment in the anterior/posterior directions (see Figures 3.5.1a and 3.5.2b). This prototype thus had greater capabilty for optimizing several variables as well as more closely simulating the A/K amputee's prosthesis.



a) perspective view.



b) side view
(Note relative position of wheels and leg section.)

FIGURE 3.5.2 WHEEL BRACKET OF THIRD PROTOTYPE

4. ASSESSMENT OF PROTOTYPES

4.1 FIRST PROTOTYPE

4.1.1 Experimental. The first prototype was tested by the author. This test was designed to determine the behavior of a linear wheel arrangement without the control of flexible knee and ankle joints.

The subject secured the knee immobilizer and Roller Blade boot onto the right leg and traveled on a smooth flat surface. The testing was conducted in two informal half hour sessions. In the first session the subject dorsal-flexed the sound ankle to compensate for the height difference described earlier. In the second session the other Roller Blade boot, with the wheels immobilized, was used to correct the difference. Several left and right turns of different radii were executed from various speeds. Stopping was attempted with and without the use of the backstop.

4.1.2 Results. The subject was able to perform each of the prescribed tasks with relative ease and found the first prototype to be a comfortable means of transportation. Control of turns at higher speed was not difficult. The use of the back stop was not instinctive but convenient once learned. There was considerable motion in the knee and ankle of the right leg. Moments were therefore applied at these points and seemed to aid in the control and balance of the device.

4.2 SECOND PROTOTYPE

4.2.2 Experimental. The performance of the second prototype was tested in a manner more formal but similar to the first. Three subjects conducted tests (one of which was the author) on a smooth, linoleum floor in a large room. Safety equipment was worn (with the exclusion of the crutch) throughout the test period.

After the height was adjusted to each subject and the constraining devices set, each subject executed several right and left hand turns as well as stops from various speeds. Stopping with and without the backstop was attempted.

4.2.2 Results. Several problems were found to exist in the use of the second prototype. Balance was diffcult . All the subjects felt unstable in both the lateral and sagital directions. There was a need to continuously lean the upper body in the anterior direction to maintain balance. Subjects felt a great deal of insecurity in the lateral direction particularly in the direction away from the sound leg. These instabilities were attributed to the misalignment of the leg of the prototype with respect to the wheel configuration (recall Figures 3.4.1 and 3.4.4). Since this alignment was not adjustable in the second prototype, it was concluded that the design and construction of a third prototype were necessary.

4.3 THIRD PROTOTYPE

4.3.1 Experimental. Before the third protoype was used to compare wheel configurations, it was necessary to establish its functionality.

The test required the execution of a variety of turns, stops and speeds. Once these basic maneuvers were executed with competence, the subject proceeded to more difficult test conditions. The variables of terrain and interference from other people were introduced. This protocol overlaps with the protocol used in comparison experiments and is described in detail in Chapter 5.

4.3.2 Results. The stability problems experienced during the use of the second prototype were alleviated in this design. The subjects had much more stability in the lateral and longitudinal directions and gained confidence and proficiency in maneuvering the prototype. The adjustment features of this prototype were also useful and several adjustments were typically made until the subject was comfortable. Subjects felt that the changes in alignment greatly aided in their performance as well as their confidence in the prototype.

The subjects all demonstrated the fine control required to move about in crowded areas. They were also successful on various terrains. Generally, the subjects traveled at speeds faster than ordinary walking. A more detailed discussion of the dynamics of the use of this prototype can be found in the following chapter.

5. COMPARISON OF WHEEL CONFIGURATIONS

5.1 EXPERIMENTAL PROCEDURE

This was the third an final experiment conducted in this research. The skateboard wheel configuration employing lean-steering was compared to the single track wheel arrangement which is steered by pivoting as well as leaning. The experimental protocol was conducted by each of three subjects on each of the wheel arrangements. The three subjects varied in age and athletic experience.

5.1.1 Criteria. The third protocol was designed to simulate agility requirements that arise in ordinary daily situations. Two types of stopping situations occur, one in which the individual has preview that a stop is required and one in which the individual is suprised and must stop spontaneously. An individual is also required to perform a wide variety of turning and weaving maneuvers. Fine control and agility are necessary to avoid obstacles, some of which may appear spontaneously.

A series of terrain features and transitions are also encountered. Transition from smooth floors to carpeted floors and riding over door moldings are some examples. Interaction with people is also a situation that often arises. Maneuvering through a crowded corridor or room presents different problems than moving through a stationary or predictable obstacle course.

5.1.2 The Experimental Protocol. The subjects were fitted with one of the prosthesis prototypes. The height was carefully adjusted, as were the angle of the thigh attachment with respect to the vertical plane of the leg and the angle of the leg with respect to the wheel base. Several readjustments were typically required before the subjects were comfortable. The thigh attachment was tightened several times to insure minimum motion. All subjects wore the prototypes on their right leg.

After the subject's fitting was complete, they were asked to move about a large room on a smooth, level, linolium floor. The saftey equipment was worn and the crutch was included. After a short practice period where the subject was allowed to become familiar with the balance requirements of each prototype and the method of propulsion in the forward direction, they were asked to execute a series of maneuvers. First they performed tight right and left handed turns (90° and greater). Next the subjects performed a series of weaving turns of large radii in both the left and right directions and a series of stops. The subjects experimented with several methods of execution for all the above activities until they found a comfortable means of control. They were asked to think about the dynamics of their actions and the comfort and ease with which these activities were performed. The subjects were also required to vary the speeds at which they traveled and asked to comment on the stability and apparent energy cost at each condition.

After the subjects became comfortable with these basic maneuvers, they progressed to more demanding conditions. New variables were introduced; changes in terrain, bumps and crowded areas. The 'advanced' conditions varied for each subject due to time constraints. All the subjects traveled along an interior corridor with a slightly less consistent terrain and a moderate amount of interference from other people. They also experimented with transition from a smooth floor to a carpeted area. This softer terrain introduced a rolling resitance. The first subject also experimented with the transition from floor to elevator. The second subject conducted a more extensive test of terrain and crowd conditions. He was required to maneuver through a heavily trafficed corridor. The second subject further tested the handling of the devices by navigating through more cluttered areas. This portion of the test was conducted on both carpeted (office area) and uncarpeted (lavatory) terrain. The subjects again commented on the stability and control of the prototypes as well as their confidence in using them.

After completing this protocol with both prototypes the subjects compared the wheel configurations in several different catagories. In addition to verbal comments which were noted throughout the testing, the subjects rated each wheel configuration on a numerical scale.

5.1.3 <u>Subject Description</u> The subjects chosen varied in age and familiarity with the research. Since it was postulated that previous experience could effect learning and therefore performance, the subjects were asked to comment on their experience and skill level in a variety of activities. The activities chosen were all single person means of locomotion requiring balance and directional control. Those requiring steering most similar to the lean-steering employed by skateboard trucks are skateboarding, water skiing and surfing. Activities whose steering and balance is most similar to that of a single track wheel configuration are Roller Blade skating and unicycling. The other activities demonstrate similarities mostly in balance and coordination skills.

The highlights of the subjects responses are noted below. Appendix A contains a more detailed summary of each subject's self-evaluation. The three subjects provided a resonable range of skill levels in the assorted activities. The first point to be noted is the high level of proficiency of first subject in unicycling as well as the majority of the listed activities. The second subject, though an excellent athelete, had little to no experience in most of the activities. Subject three, also of above average athletic skills, had a moderate amount of experience in most of the activities - except cycling where he was highly skilled.

5.2 RESULTS AND DISCUSSION

5.2.1 Overview. The subjects all expressed a positive and confident attitude toward the wheeled prosthesis approach. Both prototypes were maneuverable, safe and provided considerable mobility. In general the second and third subjects prefered the skateboard wheel configuration over the tandem arrangement. They found the skateboard wheels increased their stability. This subsequently bettered their competence in maneuvering and increased their confidence in using the prototypes. The first subject, however, decidedly favored the tandem wheel configuration. This could be attributed to this subjects extensive experience in unicycling. The first subject used her knowledge of unicylce steering to control the tandem wheel prototype. The skateboard prototype felt less stable and cumbersome her. A summary of the numerical ratings for each prototype is found in Table 1.

5.2.2 Dynamics of 'walking'. The subjects demonstrated two distinct gaits when using the prototypes. One gait, the 'scooter' gait, consists of the subject placing all their weight onto the prototype and using the sound leg to push off. During this type of gait a long coasting period is observed. Coasting requires very little energy but a considerable amount of balance. During the 'walking' gait, the user transfers more weight onto the pushing foot creating a shorter coasting stage. The subject also rolls his/her foot heel to toe, as in a normal walking gait. Both these gaits were used while wearing either prototype.

The second and third subjects found coasting and 'walking' to be easier on the skateboard wheel configuration. They both felt more stable on this configuration and thus were able to spend more time at 'rest' balanced on the prototype. For these subjects, it was difficult to find a stable point while coasting or walking on the tandem prototype. This created an uncomfortable 'jamming' of the sound leg. The subjects attempted to balance on the leg fitted with the prototype but, unsuccessful they were forced to fall back on and 'jam' their sound leg.

The increased stability of these subjects on the skateboard prototype was attributed to several geometric reasons. The skateboard geometry has a greater area of contact with the floor. The lateral motion required for the steering of the wheels has some stiffness and therefore lends some support in the lateral direction. The anterior/posterior rocking found in the tandem wheel arrangement is absent in the skateboard configuration. Thus, the skateboard wheels limit the degrees of freedom causing the second and third subjects to feel more secure in balancing.

The third subject, on the contrary, felt more comfortable coasting and walking on the tandem prototype. She was able to find a stable point while all her weight was on the prototype. Once in a coasting position she used a steering method identical to that used in unicycle riding - creating a pivoting action at the wheels by twisting the shoulders relative to the hips. The skatebaord steering system caused this subject to feel unstable while using this protoytpe. This prototype, while coasting, travels along a waving trajectory, The leaning motion used to transfer the center of gravity over the prototype initiates a turn. To coast, the user must lean back and forth to compensate for the turning effects. To the third subject this proved to be an unstable form of travel. This coupling of balancing and steering caused the first subject to feel unstable. She felt a total uncoupling of the two actions provided better control and stability.

5.2.3 Dynamics of turning and stopping. The subjects were more consistent in their assessment of turning and stopping. In general, they all agreed that left turns were much easier to perform than right turns. Each turn was accomplished by a different motion. During left turns, the weight of the subject was entirely on the sound leg and the protoytpe was simply pivoted around it. During right turns however, the subjects were forced to lean away from their center of gravity and were not able to stabilize themselves with the sound leg. It was felt that the skateboard configuration provided a more stable base for right turns than did the linear wheel configuration. The subjects often used the crutch to catch themselves while turning right particularly while using the tandem wheel prototype. The subjects felt the linear configuration was the more agile of the two. However, for the second and third subjects, the instability they felt did not allow them the confidence to utilize this advantage.

Two of the subjects felt that stopping was easier on the tandem configuration than on the skatboard configuration. There were two reasons given. One subject was dependent on the back stop attached to the tandem configuration (but not the skateboard configuration) to stop the momentum of the protctype. This was the only subject who felt the backstop was necessary. The other subject simple felt the tandem arrangement was lighter and therfore required less effort to stop. The last subject saw no difference in the ease of stopping between the two prototypes.

The subjects uniformly chose the configuration they felt most stable on as the one which they were able to control most finely. This suggested that the level of confidence and the sureness of 'footing' were critical in the users ability to control the prototypes. It was generally felt that transition from one terrain feature to another was easily accomplished on either prototype.

Table 1: SUMMARY OF THE NUMERICAL COMPARISON OF WHEEL CONFIGURATIONS
(1 is considered the lowest rating and 5 the highest)

Catagory	Subject	Rating of Configurations: Skateboard (1 2 3 4 5)	Rating of Configurations: Tandem (1 2 3 4 5)
Confidence (in safety)	1	••••••	••••••••••••
	2	••••••••••••	••••••
	3	••• ••• ••• •••	••• ••• •••
Right Turns	1	•••••••••	••••••
	2	••••••••••••	••••••
	3	••••••••••••	•••••••••
Left Turns	1	•••••••••	•••••••••••••••
	2	•••••••••••••••	••••••••••••
	3	••••••••••••	••••••••••••
Stopping	1	•••••••••	•••••••••
	2	•••••••••	••••••••••••
	3	••••••••••••	•••••••••••••••
Speed	1	••••••	••••••••••••
	2	••••••••••••	•••••••••
	3	••••••••••••	•••••••••
Balance	1	••••••	•••••••••••••••
	2	•••••••••	•••
	3	••••••••••••	•••••••••
Concentration	1	••••••	••••••••••••
	2	•••••••••	••••••
	3	••••••••••••	•••••••••
Energy	1	•••	••••••••••••
	2	•••••••••	••••••
	3	••••••••••••	•••••••••

6. CONCLUSIONS AND RECOMMENDATIONS

This study continues to support the feasibility of the concept of using wheels to improve the mobility of A/K amputees. It was demonstrated that there is more than one successful way to approach a design judging on the basis of safety, mobility and cosmesis. The utilization of the skateboard wheel configuration using a lean steering system once again proved its success as did a tandem wheel configuration steered cheifly by pivoting actions. Since the response of the subjects in assessing the configurations was varied it appears that the success of a particular configuration is dependent its particular user. It appears, however, that stability is uniformly the major issue in determining the ability of the user to increase mobility with a wheeled prosthesis. If the user does not feel stable, his ability to maneuver the device will be affected.

This allows some flexibility in the type of wheel configurations possible. A user that has good balance may feel stable enough on a prototype that is less cumbersome and smaller than a user who has less of an ability to balance. Tradeoffs could be made between stability, maneuverabilitiy and cosmetics according to the abilities and priorities of the potential user.

Further study is recommended to confirm the ability of an A/K amputee to use a wheeled prosthesis. The current prototype allows movement in the thigh 'socket' that is not available to an A/K amputee. This movement causes moments that potentially aid in balance and control of the prototype. It is unclear how much this movement aids (or hinders) the use of the prototype prosthesis. This study is at a point where the input of an amputee subject would be very useful.

APPENDIX A

SUBJECT DESCRIPTION

Subject 1
Age: 22 yrs.
Sex: Female

Experience of subjects in various single person means of locomotion requiring balance and directional control:

Activity	Experience/Skill Level
ice skating	10 yrs. (5 yrs. ago), intermediate
conventional roller skating	10 yrs., advanced beginner
Roller Blade skating	2 yrs., adv. beg.
skateboarding	2-3 yrs., adv. beg.
bicycling	18 yrs., advanced (long distances)
skiing, nordic	2-3 yrs., intermediate
skiing, alpine	2 days, adv. beg.
water skiing	10 days, adv. beg.
surfing	none
windsurfing	3 hrs., beginner
unicycling	12 yrs., expert (can travel several miles)
previous experience with original prosthesis	none

SUBJECT DESCRIPTION

Subject 2
Age: 25 yrs.
Sex: Male

Experience of subjects in various single person means of locomotion requiring balance and directional control:

Activity	Experience/Skill Level
ice skating	none
conventional roller skating	none
Roller Blade skating	none
skateboarding	none
bicycling	18 yrs., advanced (long distances)
skiing, nordic	4 yrs. (4 yrs. ago)
skiing, alpine	none
water skiing	1 hr., beginner
surfing	none
windsurfing	none
unicycling	none
previous experience with original prosthesis	none

SUBJECT DESCRIPTION

Subject 3
Age: 37 yrs.
Sex: Male

Experience of subjects in various single person means of locomotion requiring balance and directional control:

Activity	Experience/Skill Level
ice skating	few hrs., beginner
conventional roller skating	10 yrs. (22 yrs. ago)
Roller Blade skating	none
skateboarding	few hrs.
bicycling	30 yrs., advanced (long distances)
skiing, alpine	4 days, intermediate
water skiing	none
surfing	none
windsurfing	20 days, intermediate
unicycling	can travel 10 feet
previous experience with original prosthesis	none

APPENDIX B

INFORMED CONSENT DOCUMENT

Statement of Informed Consent
for Non-Amputee Subjects

As an investigator in this study, I understand all testing procedures to be used in my part as test subject. Briefly: I will perform riding tests of wheeled prosthesis designs over terrain features of various difficulty levels. I will be wearing appropriate safety devices, and initial attempts at a terrain feature will be made with a safety harness.

I understand that the purpose of this study is to develpo a mobility aid for leg amputees.

I understand that the only benefit I am to expect is the personal satisfaction that may be obtained from my contribution to the study.

I understand that I may withdraw my constent and discontinue participation in the study at any time.

I understand that, in the event of physical injury resulting from the research procedure, medical care is available through the M.I.T. Medical Department. The costs of that care will be born by my own health insurance or other personal resources. Information about the resources available at the M.I.T. Medical Department is available from Linda Rounds at 253-4902.

There is no other form of conpensation, financial or insurance , furnished to research subjects merely bacause they are research sujects. Further information may be obtained by calling Thomas Henneberry at 253-2822.

signed______________________________________

date____