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DRAFT: THE DESIGN AND TESTING OF A LOW-COST, GLOBALLY-MANUFACTURABLE, MULTI-SPEED MOBILITY AID DESIGNED FOR USE ON VARIED TERRAIN IN DEVELOPING AND DEVELOPED COUNTRIES

Amos G. Winter, V*
Department of Mechanical Engineering

Mario A. Bollini
Department of Mechanical Engineering

Danielle H. DeLatte
Department of Aeronautics and Astronautics

Harrison F. O'Hanley
Department of Mechanical Engineering

Natasha K. Scolnik
Department of Mechanical Engineering

MIT Mobility Lab
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U.S.A.

ABSTRACT

People with disabilities in developing countries often do not have access to public transportation and are forced to travel long distances under their own power on varied terrain. In this work we present the Leveraged Freedom Chair (LFC), a wheelchair-based mobility aid designed to operate in virtually any environment by optimally converting upper body power for propulsion through a variable-speed lever drivetrain. Instead of using multiple gears to change speed, the user varies mechanical advantage by sliding his hands up and down the levelers. Changing user geometry instead of machine geometry enables the LFC drivetrain to be composed of a lightweight, low-cost, single gear ratio chain drive made from bicycle components found anywhere in the developing world.

Human power and force output capabilities were used to generate the LFC drivetrain geometry. The lever system achieves a 4:1 change in mechanical advantage, equating to leverage that ranges from 0.42X to 1.65X a standard wheelchair hand rim. In comparative user trials, the LFC demonstrated operational capabilities that far exceed those of any mobility aid currently available in the developing world; it was able to cruise on smooth surfaces at 2m/s (5mph), climb muddy, grassy hills with a 1:3 slope, and navigate terrain with a coefficient of rolling resistance as high as 0.48. This operational flexibility should make the LFC usable on any terrain, from rural walking paths to within the home, and greatly increase the mobility of people with disabilities in developing countries. The LFC may also be attractive to also be attractive to wheelchair users in developed countries, as its performance breadth exceeds that of currently available mobility aids.

1 INTRODUCTION

In this work we present the Leveraged Freedom Chair (LFC), a wheelchair-based mobility aid that can be made anywhere in the world with off-the-shelf bicycle parts and cope with varied terrain ranging from steep hills to sandy roads to muddy walking paths to within the home. The motivation behind this project is to provide mobility to people with disabilities in developing countries no matter their location, travel requirements, or local environment. A mobility aid that can meet these needs is desperately needed, as 20 million people in the developing world require a wheelchair [1] but only about five percent actually have one [2]. Disability is both a cause and consequence of poverty [3]; 98% of children with disabilities in developing countries do not attend school [4], and lack of mobility can deny people essential social rights like having a job or participating in their community. Public transportation is rarely an option, as 70% of the developing world disabled live in rural areas [5]. Even if busses are available, people with disabilities are often charged double to bring their wheelchair onboard or flat-out turned away because of discrimination [6].

* PhD Candidate and author of correspondence, Phone: (617) 312-4207, Email: awinter@mit.edu

The lack of alternative transportation means most mobility aid users have to travel under their own power to get from point A to B, often on harsh terrain for multiple kilometers [6]. Products that are currently available in developing countries can not fulfill the wide usage needs of the disabled. Conventional western-styled wheelchairs, as shown in Fig. 1a, are inefficient to propel [7] and are exhausting to use for long distances on rough roads. Imported wheelchairs usually contain parts that are impossible to replace once broken. Even locally-made products rely on expensive bearings and custom components that raise the price to a level out of reach for most people in the developing world. Hand-powered tricycles (Fig. 1b), which are preferred if the user has adequate torso stability [6], are more efficient to propel than a wheelchair [7-9] and cost less due to the incorporation of standardized bicycle components. Unfortunately, tricycles are difficult to maneuver through sand and up steep hills, and are much too large to use within the home.

a. Wheelchair b. Hand-powered tricycle

Figure 1. Common developing country mobility aids

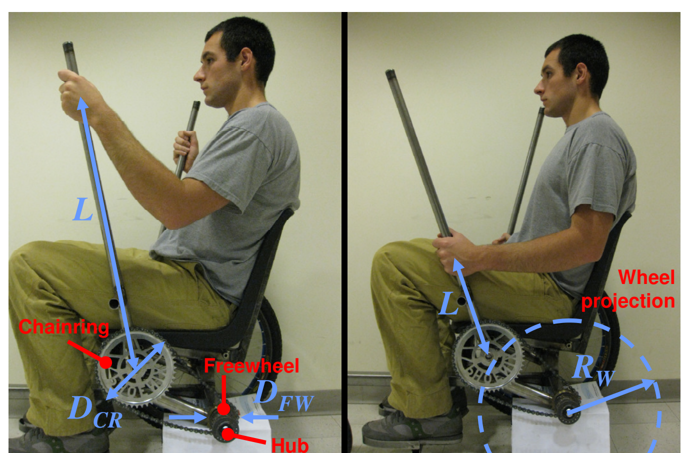
2 LEVERAGED FREEDOM CHAIR DESIGN

The LFC is designed to span the operational space between long-distance travel on rough roads and mobility in tight confines, such as in the home. This is accomplished through a lever drivetrain mounted on a three-wheeled wheelchair platform, as shown in Fig. 2. The lever system, which is discussed in the following sections, is designed to optimally convert upper body power for propulsion in a wide range of terrains. For short-range mobility, such as in an office or around a bathroom, the LFC can be converted to a conventional wheelchair by simply removing the levers. The wheel layout and rider position is derived from the Worldmade Wheelchair, designed by Motivation UK [10]. The Worldmade is a popular wheelchair in developing countries because its three wheels are always kinematically constrained with the ground. Its long wheelbase provides stability and decreases loading on the front wheel, which combined with its large diameter, increases comfort and ability to go over obstacles.

Figure 2. The Leveraged Freedom Chair

2.1 VARIABLE-SPEED, FIXED GEAR RATIO LEVER DRIVETRAIN

Imagine trying to ride a mountain bike off-road, using only one gear, and pedaling with your hands. This scenario is analogous to the trials faced by users of wheelchairs and tricycles in developing countries. Just as a multi-speed bicycle enables the user to maintain a relatively constant power output while riding on diverse terrain, a mobility aid intended for use on anything from muddy hills to smooth streets requires variable mechanical advantage. The LFC achieves a multi-speed, fixed gear ratio drivetrain with the lever system shown in Fig. 3.



a. LFC in low gear b. LFC in high gear

Figure 3. Changing mechanical advantage by moving hand position on the levers

Unlike most gear trains, which operate in varied states to obtain multiple ratios, the LFC's drivetrain exists in only one state; it is the user who changes his hand position to change the mechanical advantage of the device. If more torque at the wheel is needed to climb a hill, the user simply slides his hands up the levers and away from the pivots, as shown in Fig. 3a. If more speed is required, the user moves his hands closer to the lever pivots, as shown in Fig. 3b, achieving a greater angular deflection with every push stroke. The relationship between chair speed and hand speed is represented by Eqn. 1

$$\frac{V_{Chair}}{V_{Hand}} = \frac{D_{CR} R_W}{D_{FW} L} \tag{1}$$

where V_{Chair} is the chair velocity, V_{Hand} is the users hand velocity, D_{CR} is the chainring diameter, R_W is the wheel radius, D_{FW} is the freewheel diameter, and L is the lever length.

The fixed gear ratio offers a number of advantages over a multi-speed gear train. First, it does not require a derailleur, which is an expensive, unreliable, and fragile part in the developing world [11, 12]. Second, it enables the gear train to be lightweight. Third, all rolling elements are fabricated from bicycle parts that can be purchased in any developing country [12]. This means every moving part of the LFC is locally available and repairable by bicycle technicians. Finally, the use of bicycle parts makes the LFC inexpensive to produce; gear train parts for one chair cost \$20US, which is approximately the same price as two rear hub and bearing sets used in East African-produced wheelchairs [13]. The expected total cost of the LFC is approximately \$150-\$400US, the same price range of wheelchairs currently produced in developing countries [14-16].

The LFC is powered by pushing the levers forward. Pulling them back ratchets and resets the gear train. This actuation scheme was chosen to enable people with a large range of disabilities to propel the LFC. For example, a person with a spinal cord injury may not have control of his abdominal muscles. The pushing motion allows the rider to brace against the seat back, whereas a pulling power stroke could pull him out of the chair. Furthermore, pushing levers engages larger muscle groups than using conventional hand rims, resulting in a greater power output with less exertion [7-9]. Braking is accomplished by pulling all the way back on the levers, past the minimum angle in the actuation return stroke. This forces the small tubes protruding orthogonally from the levers, which can be seen in Fig. 2, to contact the tires. The braking motion does not tend to push the rider out of the chair, as the seat recline angle allows body weight to aid in pulling on the levers. Steering of the LFC is accomplished by either differentially powering or braking the wheels.

2.2 LEVER GEOMETRY OPTIMIZATION

The design of the LFC gear train geometry was driven by human power capabilities. Available upper body pushing power for propulsion was determined by adapting results from Woude, et al [8], and was calculated to be 19.6W with a pushing force of 58N and hand velocity of 0.38m/s. In this paper, young men were tested to find the gear ratio for a lever-powered system that would yield the highest efficiency with relatively low exertion (approximately 30% increase in heart rate from resting). This level of power output was used in Eqn. 2 to calculate the attainable velocity for long-duration travel on a variety of terrains, neglecting efficiency losses in the drivetrain.

$$\begin{aligned} P_{Human} &= P_{Drag} + P_{Rolling} + P_{Gravity} \\ &= C_D \frac{1}{2} \rho_{air} A (V_{Chair})^3 \\ &\quad + mg(V_{Chair})[\mu_{roll} \cos\theta + \sin\theta] \end{aligned} \tag{2}$$

Values used in Eqn. 2 were $C_D = 1$ [17], $\rho_{air} = 1.2\text{kg/m}^3$, $A = 0.6\text{m}^2$, rider+chair mass $m = 75\text{kg}$, and $g = 9.81\text{m/s}^2$. Road surfaces in developing countries vary from tarmac to gravel to mud to sand, corresponding to rolling friction coefficients, μ_{roll}, ranging from 0.005 to 0.5 [17, 18]. Slope angles, θ, used in this analysis were varied between 0° and 40°, just beyond the backwards tipping angle of the LFC.

Using Eqn. 1 with $V_{Hand} = 0.38\text{m/s}$ and the V_{Chair} data generated from Eqn. 2, the required lever length at each combination of rolling resistance and angle was computed. These data were compared to lever lengths that the authors could comfortably grasp, which were measured to be a maximum of L = 86cm to a minimum of L = 22cm. This comparison, shown in Fig. 4, demonstrates that for the most common road conditions, with rolling friction ranging from 0.01 to 0.1 (approximately tarmac to gravel) and slopes up to 5° (1:11 rise), the rider can propel himself at maximum efficiency. Expected velocities over these terrains, calculated with Eqn. 2, are plotted in Fig. 5.

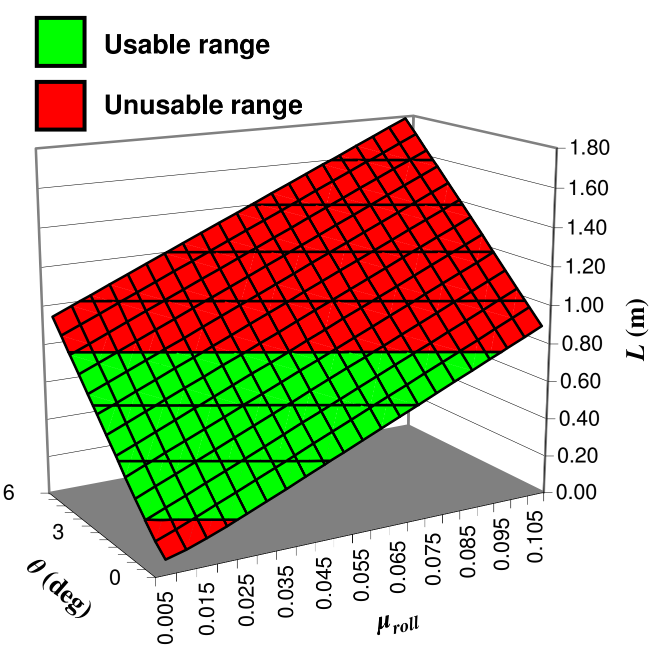


Figure 4. Required lever lengths for varying terrains at peak efficiency power output

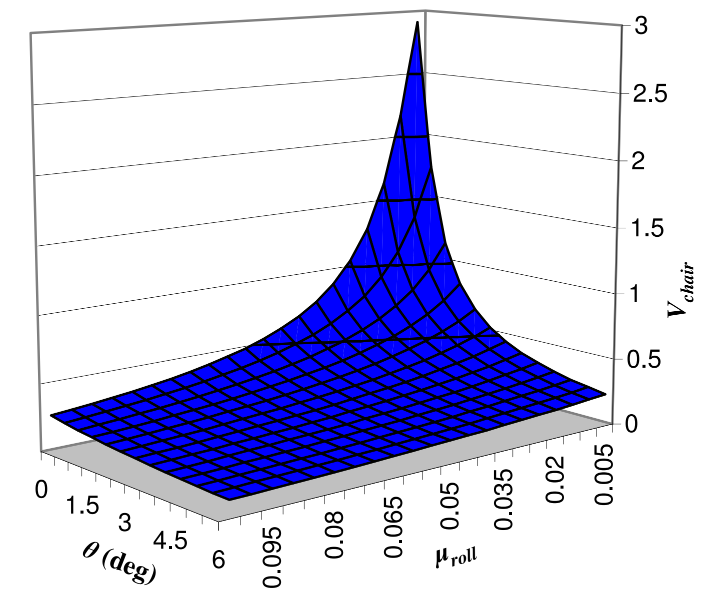


Figure 5. Attainable velocity at peak efficiency power output

On high resistance surfaces, such as sand or steep hills, an LFC rider may have to compromise efficiency in order to achieve high torque at the wheels. In these situations the chair velocity will be approximately zero, reducing Eqn. 2 to Eqn. 3,

$$F_{Resist} = mg\left[\mu_{roll}\cos\theta + \sin\theta\right] \tag{3}$$

where F_{Resist} is the total resistance force acting on the chair. Rearranging Eqn. 1 for force instead of speed transfer, and neglecting drivetrain efficiency, yields Eqn. 4,

$$\frac{F_{Resist}}{F_{Hand}} = \frac{D_{FW} L}{D_{CR} R_W} \tag{4}$$

where F_{Hand} is the pushing force exerted on the levers. By combining Equations 3 and 4, the required lever length for any terrain condition can be solved as a function of F_{Hand}.

Maximum attainable pushing force was determined through US military tests on aircraft control sticks [19] – an interface geometrically similar to the LFC levers. For males in the 50th percentile of the population, this force was measured to be 356N. Using F_{Hand} = 356N, the required lever length at every plausible operating point was computed, and is shown in Fig. 6.

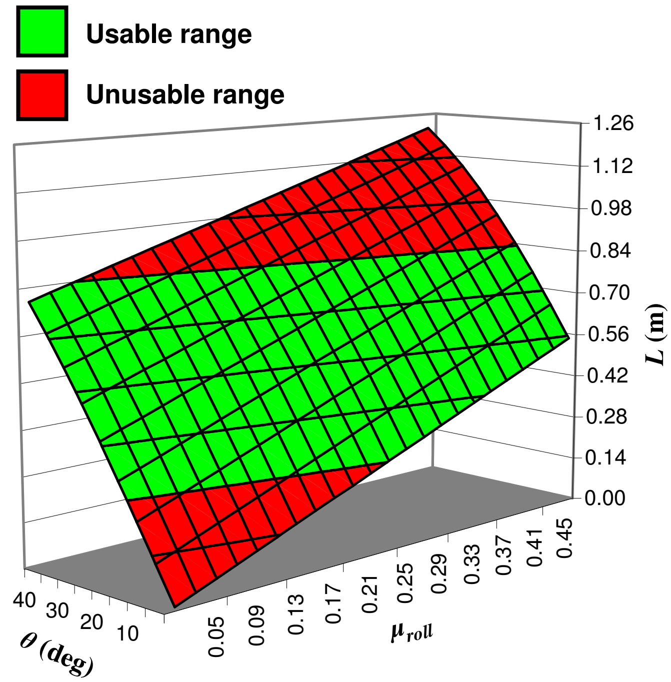


Figure 6. Required lever lengths for varying terrains at peak force output

The drivetrain configuration used to generate Figures 4-6 was composed of a 36-tooth chainring and a 20-tooth freewheel. The most common chainring sizes available in developing countries are 52, 48, 44, 36, and 32 teeth and the most common and robust freewheel size is 20 teeth [12]. The 36/20 chainring/freewheel combination was chosen because it maximized the operation range between high-speed and high-torque performance.

The results presented in Figures 4-6 demonstrate that one set of levers, which can be grasped between 22cm to 86cm from the pivot, will enable an LFC rider to travel on virtually any terrain, the most common of which at high speeds and efficiency. To further illustrate the breadth of the LFC's capability, the effective lever arm produced by the drivetrain can be compared to a conventional wheelchair hand rim through an effective hand rim radius, *R'*, which is defined in Eqn. 5.

$$R' = \frac{L D_{FW}}{R_{HR} D_{CR}} \tag{5}$$

Eqn. 5 is plotted in Fig. 7 using R_{HR} = 29cm, the hand rim radius from the wheelchair in Fig. 1a, with the LFC's gear ratio and lever length range. Fig. 7 shows that the LFC drivetrain is able to vary by 4:1 in mechanical advantage, effectively producing a 0.42X to 1.65X hand rim.

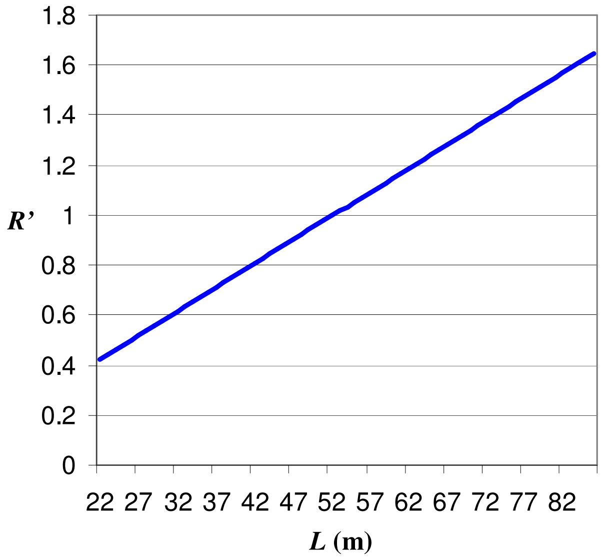


Figure 7. Effective hand rim radius vs. positions on LFC levers

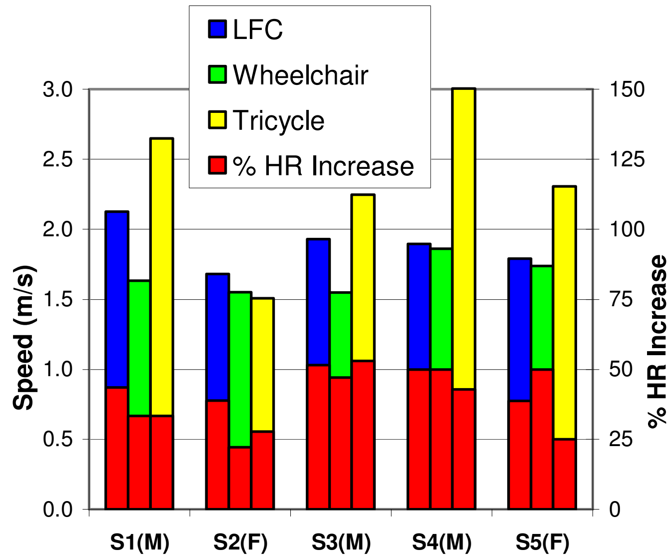


Figure 8. Average velocity and heart rate increase for long distance trials

3 LFC TESTING AND COMPARISON TO EXISTING MOBILITY AIDS

To compare the performance between the LFC and existing developing country mobility aids, the LFC was tested in various environments and operating conditions against the East African wheelchair and tricycle pictured in Fig. 1. The first trial was an endurance test on level, smooth terrain. Five test subjects, three male and two female, ranging from age 22-29, none of whom regular wheelchair users, rode each mobility aid 0.87km (0.54miles) on a course through the MIT campus. The subjects were told to travel at a comfortable, relaxed pace that they could maintain throughout the trial. Average velocity and exertion, measured through increased heart rate (HR) from resting, was recorded for each subject and assembled into the chart in Fig. 8.

The mean LFC velocity for the team was 1.89m/s, nearly the exact velocity predicted by Fig. 5 for flat, smooth terrain and moderate levels of exertion. The wheelchair was 11.7% slower with an average velocity of 1.67 m/s, and the tricycle was 24.3% faster at 2.34m/s. Percent increased heart rate from rest for the LFC, wheelchair, and tricycle were 44.5%, 40.5%, and 36.4%, respectively.

These results show that the LFC is faster than a wheelchair on flat, smooth surfaces for relatively the same amount of exertion, but looses out to the tricycle. Qualitatively, all of the test subjects reported that the LFC does not strain the shoulder muscles as much as the wheelchair. Additionally, the subjects found that they were able to add propulsion power to the LFC by engaging their abdominal muscles.

The second test was a hill climb trial to measure high power output performance. The hill used was a stepped, concrete indoor ramp composed of 1:12 slope sections, with an overall run of 42.1m and rise of 2.9m. The subjects rode each mobility aid up the ramp as fast as possible. Average velocity and increased in HR were recorded for each trial and compiled into Fig. 9.

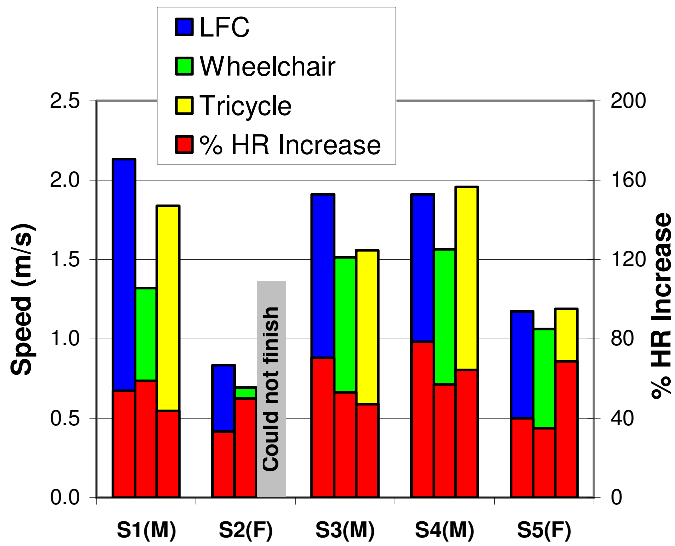


Figure 9. Average velocity and heart rate increase for hill climb trials

The LFC had the fastest team-averaged velocity up the ramp at 1.59m/s, with the wheelchair 22.7% slower at 1.23m/s and the tricycle 17.9% slower at 1.31m/s. The exertion levels for each mobility aid were similar, with increased heart rate from rest for the LFC, wheelchair, and tricycle 55.3%, 50.8%, and 55.9%, respectively. These results indicate that the LFC can deliver power at high resistances more efficiently than the other mobility aids. The wheelchair and tricycle could not produce as high mechanical advantage as the LFC, resulting in larger pushing forces, slower arm speed, and wasted power. The tricycle was geared so high that subject S2(F) could not make it up the ramp.

The final tests were conducted outdoors on ultra-high resistance surfaces in order to simulate the limits of what could be encountered in a developing country. Figure 10 shows the LFC traveling through snow, with a measured coefficient of rolling resistance that averaged from 0.21 to 0.34, with peaks as high as 0.48. The three subjects who tested the LFC in this condition were easily, although slowly, able to make progress over the ground by grasping high on the levers. Both the wheelchair and tricycle were impossible to propel through the snow. The wheelchair was geared too high, and the wet hand rims were too slippery to push effectively. The tricycle was also geared too high and did not have enough loading on the front wheel to maintain traction.

Figure 10. The LFC traveling on snow

Figure 11 shows the LFC climbing a 17.6° slope (1:3.1 rise) on wet, muddy grass. To put the formidability of this slope in perspective, the maximum allowable rise of a smooth wheelchair ramp is 1:12 according to ADA regulations [20].

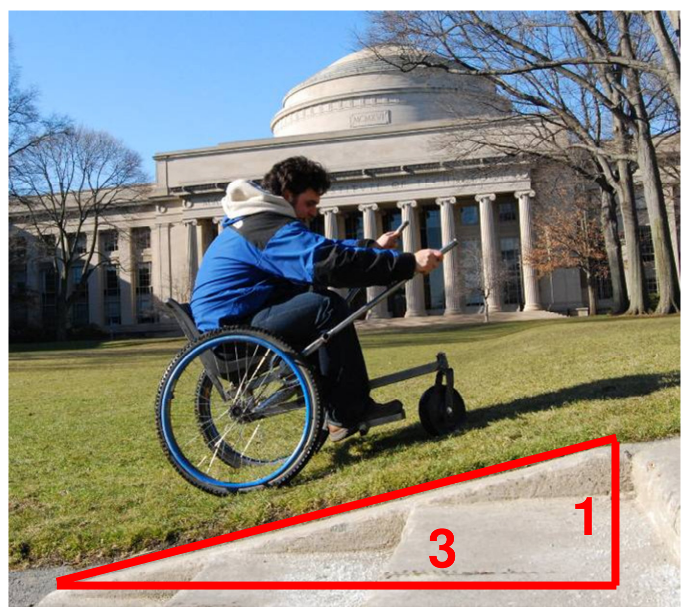


Figure 11. LFC going up 1:3 rise during hill climb trials

4 CONCLUSION AND FUTURE WORK

The LFC is a mobility aid that that is capable of traversing virtually any terrain encountered in the developing countries. The variable mechanical advantage attained from the lever drivetrain enables an LFC user to travel quickly and efficiently on smooth, flat roads and produce enough torque to conquer steep hills and soft ground. The single-speed, bicycle component drivetrain allows the LFC to be built and serviced anywhere in the world at prices similar to existing mobility aids. We are confident that the efficiency, compact size, and operational flexibility of the LFC will completely fulfill the mobility needs of people with disabilities in developing countries. Furthermore, the LFC has significant potential as a new product in developed countries, as its range of capabilities extend beyond those of any mobility aid currently available.

In August 2009 an updated LFC prototype will be taken to Africa for four-month long trials with the Association for the Physically Disabled of Kenya (APDK). This new version of the LFC will include removable levers and a fully supportive wheelchair seat and cushion. Four prototypes will be manufactured with APDK and distributed to regions of Kenya with differing terrains. User feedback will be collected in January 2010 and used to refine the design. When the design is finalized we plan to start LFC production through APDK and other developing country wheelchair manufacturers.

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