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THE DESIGN, FABRICATION, AND PERFORMANCE OF THE EAST AFRICAN TRIAL LEVERAGED FREEDOM CHAIR

Amos G. Winter, V[*]
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: awinter@mit.edu

Mario A. Bollini
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: mbollini@mit.edu

Danielle H. DeLatte
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: ddelatte@mit.edu

Benjamin M. Judge
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: benj_19@mit.edu

Harrison F. O'Hanley
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: hohanley@mit.edu

Jonathan L. Pearlman
Human Engineering Research Laboratories
University of Pittsburgh
Pittsburgh, PA 15206
Email: jlp46@pitt.edu

Natasha K. Scolnik
MIT Mobility Lab
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: tish@mit.edu

ABSTRACT

The Leveraged Freedom Chair (LFC) is a lever-powered, wheelchair-based mobility aid designed specifically for use in the developing world. Its drivetrain optimally converts upper body power in a wide range of terrains, giving the LFC operational capabilities that extend beyond those of currently available mobility products. In this work we present the design and analysis process used to create an LFC for trial in East Africa. All of the moving parts in the LFC are made from bicycle components and the entire chair can be fabricated without any machining processes. This allows the LFC to be manufactured for the same price as existing mobility aids and repaired anywhere in the developing world. Eight prototypes were produced in Kenya during August 2009, with six distributed to mobility aid users throughout East Africa. After four months of testing, the subject-averaged propulsion efficiency using the LFC was 20% greater than that of existing mobility products. Performance results and feedback from the subjects indicate that the LFC is ideally suited for active wheelchair users who require the seating and postural support of a wheelchair, and who desire to travel on rough terrain under their own power. Test subjects' input was also used to codify future improvements to the LFC design, including narrowing the stance of the chair and lowering the rider's center of gravity.

INTRODUCTION

The Leveraged Freedom Chair (LFC) is a lever-powered, wheelchair-based mobility aid designed specifically for use in the developing world. The drivetrain enables an LFC user to negotiate varied terrain ranging from steep hills to sandy roads

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[*] Address all correspondence to this author.

to muddy walking paths. For indoor use, the LFC can operate as a regular push rim wheelchair by simply removing the levers. The motivation behind this project is to create a single mobility aid that fully meets the usage requirements of people with disabilities in developing countries and transcends the capabilities of currently available technology. Western-styled wheelchairs are inefficient to propel [1] and are exhausting to use for long distances on rough roads. Hand-powered tricycles, which are preferred if the user has adequate torso stability [2], are more efficient to propel than a wheelchair [1, 3, 4], but are difficult to maneuver through sand and up steep hills and are much too large to use within the home. There is great demand for a device like the LFC, as 70% of the 20 million people in the developing world who require a wheelchair but do not have one live in rural areas [5-7].

Instead of using multiple gears to change speed, an LFC user varies mechanical advantage by sliding his or her hands up and down the levers, as shown in Fig. 1. 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 [3, 8] were used to determine a lever size and drivetrain geometry that enables the user to efficiently travel on smooth surfaces and gentle grades, and produce enough torque to overcome harsh terrain. 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 initial trials, the LFC demonstrated capabilities that 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 [9].

Figure 1 MOVING HAND POSITION TO CHANGE MECHANICAL ADVANTAGE a) Placing hands high on the levers generates high torque and an effective low gear. b) Placing hands low on the levers creates high angular velocity in the drivetrain and an effective high gear.

This paper describes the design process and analysis used to create an LFC prototype that was tested in East Africa during a four-month trial spanning from August 2009 to January 2010. Trial subjects' performance and survey results are also presented in the paper. East Africa was chosen as the trial location because it contains members of the LFC's intended user population. Additionally, it is home to our partner on the project, the Association for the Physically Disabled of Kenya (APDK) [10], which offered its wheelchair workshop for production of the trial chairs and identified clients who wanted to test the LFC.

DESIGN AND ANALYSIS OF THE EAST AFRICAN TRIAL LFC

The following design requirements were defined at the onset of the East African Trial LFC design:

- Manufacturable and repairable virtually anywhere in the developing world
- Withstand harsh environments, including mud, sand, and rocky terrains
- Competitively priced with existing, locally-made mobility products
- Usable as a wheelchair when levers are removed
- Include necessary postural support and cushioning of a wheelchair

The LFC geometry is based on the Worldmade wheelchair designed by the Motivation Charitable Trust [11]. The Worldmade is intended for outdoor use; its three wheels make it kinematically constrained with the ground, as to avoid the rocking instability experienced by conventional four-wheeled wheelchairs when one wheel lifts in the air. Its long wheelbase makes it nearly as stable in side tipping as four-wheeled chairs. As Motivation are experts in seating design, the LFC rider geometry was also adopted from the Worldmade.

All moving parts on the LFC are made from bicycle components, as shown in Fig. 2. This construction strategy was chosen because bicycles, as well as part suppliers and service shops, are ubiquitous in the developing world. By collecting or inspecting bicycle part samples in Kenya, Tanzania, Zambia, Philippines, Thailand, Vietnam, Guatemala, and Nicaragua [12], as well as conferring with other developing country wheelchair groups [10, 13], we identified components from single-speed, steel frame bicycles derived from early 20th century safety bicycles [14, 15] as the most prevalent in the developing world and appropriate for incorporation into the LFC. These components are produced by the millions by manufacturers such as Avon in India [16] and Phoenix in China [17], and sell wholesale for approximately $1US/lbs [12].

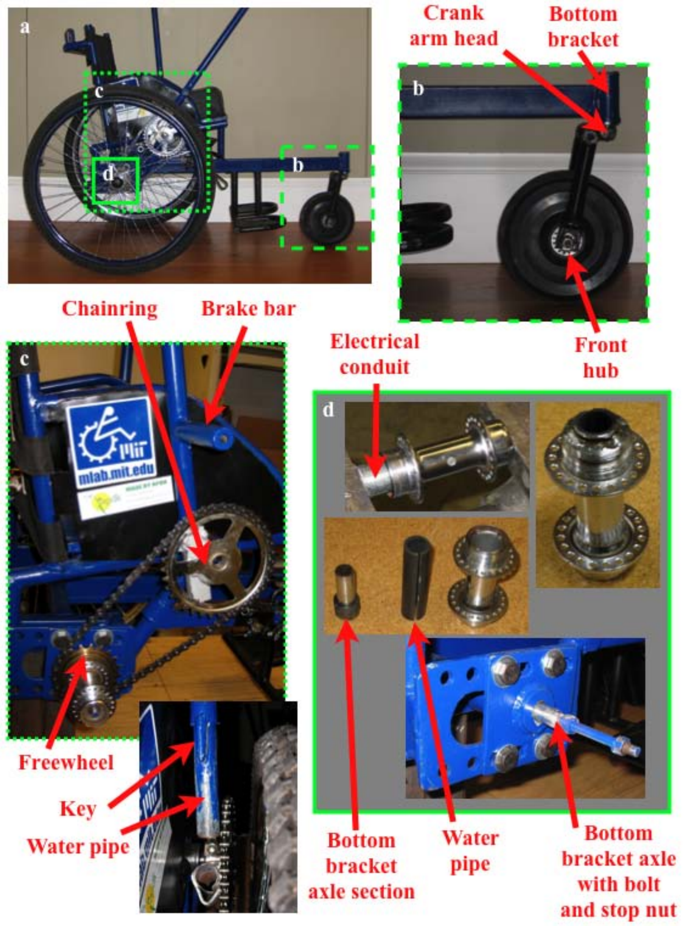

Figure 2 LFC BICYCLE PART CONSTRUCTION. a) All areas of the LFC with moving parts. b) The front caster assembly. c) Lever coupling to drivetrain made from water pipe. d) The rear hub and axle assembly, with hub inserts made from electrical conduit and water pipe.

Front Caster Assembly Design

The front caster swivel in Fig. 2b is constructed from a bottom bracket assembly. To take advantage of the cotter pin coupling that fixtures the bottom bracket axle to the pedal crank arms, the caster fork bridge incorporates the head of a crank arm. A steel strap wrapped and welded around the fork bridge evenly distributes torque and enables the fork to be made from 25mm OD, 1.2mm wall thickness mild steel lightweight tubing. Under a chair+rider load of 100kg, this design has a safety factor of 100 for torsional failure, calculated with the Tresca Yield Criterion [18] and a yield strength of 330MPa for 1020 steel [19].

The fork geometry (caster angle, trail) was adopted from the Worldmade chair, as was the molded rubber caster wheel [11]. A bicycle front hub, which is pressed into the rubber wheel, serves as the caster bearing. Pressing bicycle hubs into molded rubber wheels is a process already used by local wheelchair manufacturers, as is molding the rubber directly onto a bicycle hub [10, 13, 20].

Levers, Couplings, Brakes, and Drivetrain Design

The bottom of each lever is made from sections of half-inch schedule 40 water pipe, as shown in Fig. 2c. The water pipe slides into couplings on the drivetrain chainrings. The levers are keyed to align the brake bars perpendicular to the wheels. Pushing forward on the levers provides the power stroke; pulling back ratchets the freewheels on the rear hubs. The brakes are applied by pulling the levers back to approximately five degrees beyond vertical, which pushes the brake bars against the tires.

The levers are made from 25mm OD, 1.2mm wall thickness mild steel lightweight tubing. The water pipe used in the coupling extends 15mm inside the lever. This increases the area moment of inertia at the bottom of the lever, where the highest moments are applied. Considering a max pushing load of 356N, corresponding to the 50% male [8], acting at the lever midpoint - 40cm from the lever pivot (25cm along the 25mm OD section of tubing) - the resulting safety factor for the lever is two. A higher safety factor was not sought in order to minimize the rotational inertia of the levers. Additionally, ductile failure of the levers would not result in a catastrophic failure that could harm the rider.

The levers rotate on two bottom bracket axles, whose housings are welded into the LFC frame. Concentrating most of the lever/coupling/chainring mass about the pivot reduces the rotational inertia of the system, which improves propulsion efficiency by minimizing inertial losses caused by accelerating/decelerating the levers when changing pushing/pulling direction.

Rear Hub Design

Bicycle hubs provide an ideal interface between an axle and a spoked wheel. However, wheelchair wheels must be cantilevered from the chair for handrim clearance, whereas bicycle hubs are designed to be simply supported, such as by a fork. Figure 2d depicts how a bicycle hub is used to make a rear hub of the LFC. The hubs are strengthened by first inserting one-inch electrical conduit, and then half-inch schedule 40 water pipe. Both of these materials are commonly found in hardware stores or steel companies in the developing world [21]. The water pipe is slit axially and pressed onto a section of bottom bracket axle before it is inserted into the hub. When the hub is welded and the axle section is removed, the resulting hub inner diameter forms an interference fit with a bottom bracket axle, which is used as the rear axle in the LFC. A bolt is welded to the end of the axle, which passes through the hub once the two are assembled. A stop nut welded to the bolt positions the hub correctly on the axle, and a lock nut secures the hub in place. A conventional bicycle freewheel, used to transfer power to the wheel from the LFC drivetrain, is threaded onto each hub and secured with a tack weld.

The safety factor for the rear axles was calculated by comparing loads on the LFC to those exerted on the same components when used on a bicycle. The force exerted on the bicycle pedal acts at a moment arm of 9cm away from the bottom bracket bearing; the main radial force on an LFC wheel acts at 5.5cm away from the bearing. Assuming, during an impact (such as jumping off a curb), that all inertial loads are transferred to the axles, and that the rider's weight is approximately the same for both cases, the bending stress in the LFC axles will be 1.6X less than that in the bicycle bottom bracket axle.

Frame Loading and Material Choice

The chainring axles experience the highest non-impact loads in the LFC, due to forward and lateral pushing forces on the levers, and chain tension on the order of 1000N. To prevent deflection of the axle, which could cause the chain to derail, the axle bearing housing is built into a 3-dimensional truss within the frame. Figure 3 shows how forward and vertical deflections are mitigated via the seat tubes and the diagonal members that run from the chainring axle bearing housings to the rear wheel bolt plates. Lateral and rotation stiffness is bolstered by a cross beam that is welded to both bearing housings and runs under the seat.

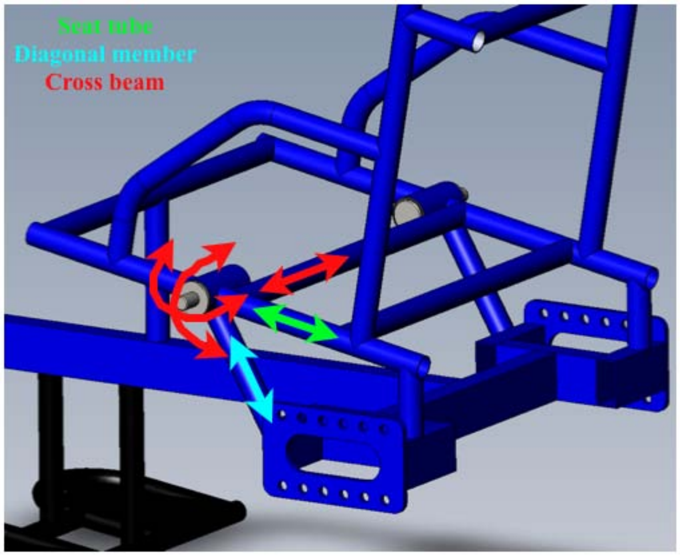

Figure 3 DIRECTIONAL FRAME STIFFNESS. LFC frame members make a truss that provides a stiff support for the lever/chainring pivot axles. Stiffness contributions of each member are color-coded.

The LFC is constructed from materials commonly available in developing countries: mild steel, wood, furniture foam, and textiles. Aluminum and titanium are either unavailable, too expensive, unworkable because of the lack of appropriate welding equipment, or of unreliable quality. The highest stress in the frame occurs in the cantilevered tube that supports the front caster. Using available tubing sizes in East Africa [21], the cross-sectional geometry with the highest strength to weight ratio and safety factor of six or more (based on static loading) was identified as 25mm X 50mm rectangular box tubing with 1.2mm wall thickness. This safety factor was chosen by considering: 1) the tube would fail in bending; 2) failure could result in injury to the rider; and 3) 6X static loading on the front wheel is conservative, as impacts, such as drops off curbs, are absorbed primarily by the rear wheels [22].

FABRICATION AND ENDURANCE TEST RESULTS

The LFC underwent a 200,000 cycle double-drum test [23] at Whirlwind Wheelchair International in June 2009. At 99,061 cycles the left rear wheel bearing failed. Upon inspection, it was determined that the cause of failure was plastic deformation of the outer bearing race. During the production of this LFC prototype, the failed bearing race was heated red-hot from nearby welding. This most likely annealed the race, causing it to fail. After the bearing cups were replaced, the LFC prototype completed the double-drum test without incident. All of the bearings in subsequent prototypes have been assembled after welding and no further failures have been experienced.

In August 2009, the authors, in collaboration with APDK, produced eight LFC trial prototypes in Kenya, two of which are shown in Fig. 1. This exercise proved that the LFC could be completely manufactured with developing country tools and materials. The total cost per chair, including 30% overhead for labor and electricity, was $195.28, which is in the $150 to $300 price range of other locally-made wheelchairs [10, 20, 24].

LFC TRIAL IN EAST AFRICA

Six LFC prototypes were distributed throughout East Africa for testing with full-time mobility aid users from August 2009 to January 2010. The four Kenyan subjects were chosen by APDK. The other two subjects are wheelchair manufactures in Tanzania and Uganda who are also collaborators on the LFC project. The subjects were chosen for their wide range of demographics, disabilities, and local terrain, as shown in Table 1. All of the subjects were required to have an existing, functioning mobility aid to use in the event that the LFC became unsafe, uncomfortable, or dangerous. Each LFC was custom-fit to its user, following the WHO's *Guidelines for the Provision of Manual Wheelchairs in Less Resourced Settings* [25]. The trial was approved by both MIT's and APDK's Institutional Review Boards.

Table 1 TRIAL SUBJECT INFORMATION

Subject ID	Description	Existing Mobility Aid
M1	Young adult man. Active wheelchair user. Sustained spinal cord injury.	Locally-produced fixed frame, three-wheeled wheelchair
F1	Adult woman. Active wheelchair user. Had polio.	Imported four-wheeled folding wheelchair
M2	Young adult man. Active tricycle user. Had polio.	Locally-produced hand-powered tricycle
M3	Young adult man. Active tricycle user. Had polio.	Locally-produced hand-powered tricycle
F2	Adult female. Very limited mobility. Wheelchair user. Sustained stroke.	Imported four-wheeled folding wheelchair
F3	Adult female. Active wheelchair users. Had polio.	Locally-produced four-wheeled folding wheelchair

Comparative User Feedback

At the beginning of the trial, each subject was asked to rate the performance of his or her current mobility aid in a variety of terrains and conditions. At the end of the trial the subjects were asked the same questions about the LFC's performance. Figure 4 shows the results of this survey. Values range from 1 = very bad to 5 = very good.

Figure 4g shows that overall, the LFC scored distinctly higher in off road conditions, including footpaths, hills, muddy/sandy soil, and extremely rough/uneven terrain. Interestingly, the contrast in performance was greatest for the active wheelchair users, shown in Fig. 4h, with the LFC rating significantly higher for long distance and off road travel, and much lower than other wheelchairs for indoor use. Indoor maneuverability was an issue for all of the test subjects, with none regularly using the LFC indoors. All of the subjects complained that the LFC is too wide to easily fit through doorways. The extra width is attributable to the lever drivetrain, which, in its current embodiment, requires the wheels to be set out approximately three inches beyond the width of a standard wheelchair of the same seat size.

Another complaint voiced by five of the test subjects was that the LFC felt like it could tip backwards easily. In its current form, the chair is balanced like an active wheelchair so the user can easily wheelie (balance on the rear two wheels) when the levers are removed. Active wheelchair users often pull wheelies to pop their front wheels over obstacles. The third most common complaint, reported by four of the subjects, was that the LFC is too large to take on public transportation. Neither tricycle user made this observation, most likely because tricycles are larger than the LFC and also difficult to transport.

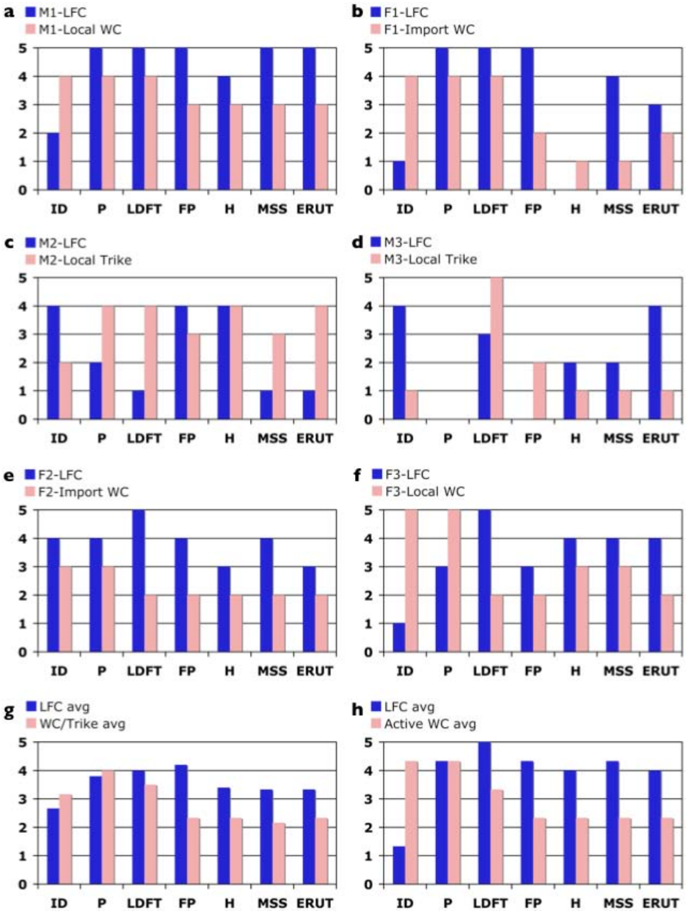

Figure 4 SURVEY RESULTS OF THE LFC VS CURRENT MOBILITY AIDS. a-f) Results of each subject comparing the LFC to his/her existing mobility aid. g) Averages of all subjects. h) Averages for active wheelchair users. ID = Indoor; P = Pavement; LDFT = Long distances on flat terrain; FP = footpaths; H = Hills; MSS = Muddy/sandy soil; and ERUT = Extremely rough/uneven terrain.

LFC Operational Performance

At the culmination of the trial, performance testing was conducted on each subject while using the LFC and his or her conventional mobility aid on a representative daily commute. Subject F1 abstained from these tests because three months into the trial she was hospitalized with a lung illness and was advised by her doctor to stop using the LFC. As the subjects traveled along their course, heart rate and distance data was recorded every 30sec using a heart rate monitor [26] and distance measuring wheel. Subject M2 was too fast to walk beside while riding his tricycle. His heart rate was collected via an onboard data acquisition system and the distance measuring wheel was attached to his tricycle with a video camera pointed at the counter.

Figure 5 shows performance data for all of the trials. The horizontal axis denotes completed fraction of the course, D^*, defined by Eqn. 1.

$$D^* = \frac{\text{Distance traveled}}{\text{Total distance}} \tag{1}$$

The vertical axis denotes power efficiency, P^*, which is defined by Eqn. 2.

$$P^* = \frac{\mu m g V}{HR^*}$$

$$HR^* = \frac{HR_{current}}{HR_{resting}} \tag{2}$$

Where μ is the coefficient of rolling resistance, m is the total mass of the user + mobility aid, g is the acceleration due to gravity, V is the velocity of the mobility aid, and HR is heart rate. The coefficient of rolling resistance was measured for each chair on level ground with the same characteristic surface roughness as the majority of the test course.

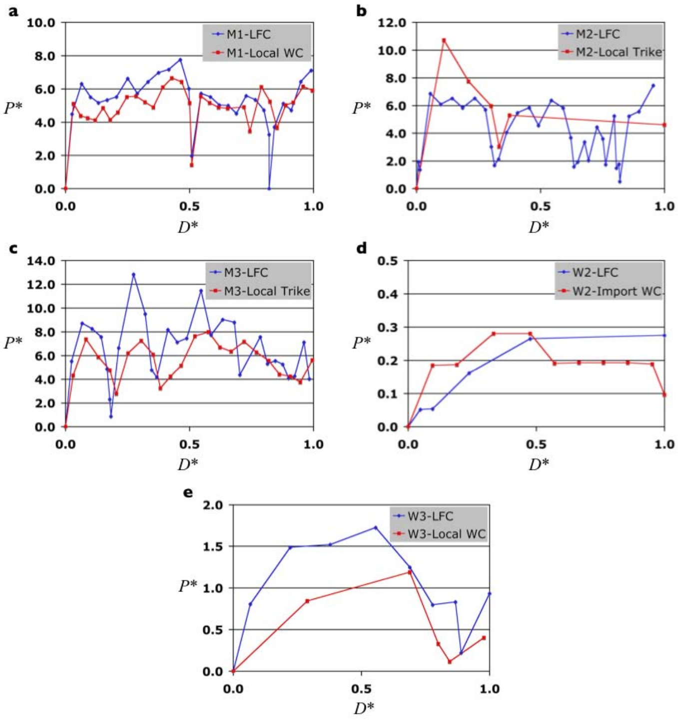

Figure 5 POWER EFFICENCY TESTS. a-e) power efficiency for each subject using the LFC and their conventional mobility aid.

The metric of comparison P^* was chosen because $\mu m g V$ is an approximation of mechanical output power and HR^* can be used as a measure of exertion. It is important to note that P^* does not include power expended due to elevation changes. All subjects' test courses were on mostly level ground, with the exception of M3. For all but M3, elevation changes should play a minimal role in power efficiency. In the case of M3, uphill and downhill velocities were similar, as road roughness prevented free coasting. Furthermore, M3 traveled in a circle, starting and ending at the some point and elevation. Thus, power variations due to gravity should cancel over M3's trial and P^* should be reasonably accurate. Table 2 provides a summary of the test results, including the ratio of mean power efficiencies for both devices used in each trial.

Table 2 PERFORMANCE TEST SUMMARY

Subject ID	**V avg LFC (m/s)**	**V avg WC/Trike (m/s)**	**Dist (m)**	**Terrain**	$\frac{\overline{P^*_{LFC}}}{\overline{P^*_{WC/Trike}}}$
M1	1.20	1.17	1061	Dirt road	1.10
M2	1.03	2.33	1021	Tarmac + dirt road	0.82
M3	1.0	1.33	896	Hilly, rough dirt road	1.25
F2	0.12	0.07	21	Flat, smooth concrete	1.04
F3	0.17	0.29	45	Dirt road	1.77

DISCUSSION

As shown in Table 2, all subjects, other than M2, experienced an increase in power efficiency, ranging from 4% to 77%, over their existing mobility aids. The lowest increase was for F2, who cannot be classified as an active wheelchair user, as she has very limited strength in her upper body and requires assistance to move in most every context. In both the LFC and her wheelchair, she struggled to travel down a flat, smooth concrete hallway during her performance test. The average increase in power efficiency for all users was 20%.

The two tricycle riders, M2 and M3, appear to benefit the least from the LFC. M2 had a much higher power efficiency and over 2X greater mean velocity with his tricycle than the LFC. Although M3 scored 25% higher power efficiency in the LFC, he was 33% faster in his tricycle. Furthermore, M2 and M3 rated their tricycles higher than the LFC for long distance travel on flat terrain, with M2 scoring his tricycle better than the LFC in most every context. These two subjects both choose to use a tricycle over a wheelchair, presumably because it gives them better long-range mobility. Both also do not require the seating and postural support provided by a wheelchair, as they retained lower extremity sensation and abdominal control after polio. Furthermore, both have some mobility without their tricycles; M2 can walk short distances using crutches and M3 agilely crawls around his shop and home by supporting himself on one leg and his hands. Crawling and crutches provide a level of mobility in tight indoor confines and over obstacles, like stairs, that could never be equaled by a wheelchair or the LFC. Thus, M2 and M3 have chosen mobility aids (tricycles) that are appropriate for their disability, local environment, and lifestyle.

CONCLUSIONS AND FUTURE WORK

Although a study with six subjects does not yield a broad data set, the results presented in this paper give insight into how well the LFC will serve its intended user group. The data indicate that the LFC, when fully developed to a marketable product, will be most appropriate for active wheelchair users who require the seating and postural support of a wheelchair and who desire the long distance, rough terrain mobility offered by the lever drive. Additional performance tests are planned for active wheelchair users in both the US and abroad, in order to broaden the data set and more accurately assess the LFC's strengths and shortcomings.

The next generation LFC prototype will have a reduced width to match the proportions of existing developing country wheelchairs. All female subjects in the trial suggested that the seat be lowered; currently it is three to four inches higher than other wheelchairs. Lowering the seat will aid in reducing backwards tippiness while not affecting downhill pull on side slopes.

This trial proved that the LFC can be built in developing countries for approximately $200, the same price as existing mobility products. None of the trial chairs experienced significant mechanical problems. Repairs that were required, such as fixing tire punctures and replacing a cotter pin, were easily accomplished by local bicycle technicians. In this trial, the LFC demonstrated that its off road and long distance capabilities exceed those of existing wheelchairs. Through continued development, principally by improving indoor performance, we are confident that the LFC will greatly enhance the mobility of people with disabilities in developing countries.

The work presented in this paper would be impossible without our collaborators and the stakeholders who tested LFCs in East Africa. Only so much international development engineering can be accomplished in the lab; the most valuable lessons were learned while working side-by-side with APDK's technicians and receiving feedback first-hand from trial subjects. Participatory development is a critical facet of every MIT Mobility Lab project. It ensures that technology developed actually meets intended needs, and that designs are properly vetted before deemed appropriate. Furthermore, co-creation with local partners provides a valuable lesson about the power of cross-cultural collaboration; the LFC project demonstrates how combining students' quantitative abilities with the intimate cultural, manufacturing, and environmental knowledge of community partners like APDK enables all participants to leverage each others' skills and produce greater outcomes together than either could alone.

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