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**STAKEHOLDER-DRIVEN DESIGN EVOLUTION OF THE LEVERAGED FREEDOM
CHAIR DEVELOPING WORLD WHEELCHAIR**

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ABSTRACT

The Leveraged Freedom Chair (LFC) is a low-cost, all-terrain, variable mechanical advantage, lever-propelled wheelchair designed for use in developing countries. The user effectively changes gear by shifting his hands along the levers; grasping near the ends increases torque delivered to the drivetrain, while grasping near the pivots enables a larger angular displacement with every stroke, which increases angular velocity in the drivetrain and makes the chair go faster. This paper chronicles the design evolution of the LFC through three user trials in East Africa, Guatemala, and India. Feedback from test subjects was used to refine the chair between trials, resulting in a device 9.1 kg (20 lbs) lighter, 8.9 cm (3.5 in) narrower, and with a center of gravity 12.7 cm (5 in) lower than the first iteration.

Survey data substantiated increases in performance after successive iterations. Quantitative biomechanical performance data were also measured during the Guatemala and India trials, which showed the LFC to be 76 percent faster and 41 percent more efficient during a common daily commute and able to produce 51 percent higher peak propulsion force compared to conventional, pushrim-propelled wheelchairs.

INTRODUCTION

The Leveraged Freedom Chair (LFC) is a lever-propelled mobility aid that is designed for use on the varied terrain encountered in developing countries (Fig. 1A). The motivation behind the LFC project is to create a single mobility aid that can fully meet the usage needs, both indoors and outdoors and in terms of seating and postural support, of people with disabilities in

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developing countries and that transcends the capabilities of currently available products. The most commonly available mobility aids in the developing world are conventional, western-styled wheelchairs and hand-powered tricycles. Pushrim-propelled 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 on soft ground and up steep hills, and are much too large to use within the home. There is tremendous demand for a device like the LFC, as 70 percent of the 20 million people in the developing world who require a wheelchair live in rural areas [5, 6], where rough roads and muddy walking paths often provide the only connection to community, employment, and education.

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 (Fig. 1B). Pushing forwards on the levers propels the chair; pulling back ratchets the drivetrain and resets it for the next stroke. Pulling all the way back engages the brakes, which are the small bars that protrude from the levers and rub against the tires. Human power and force output capabilities 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 [7, 8]. Varying mechanical advantage by changing the user's geometry (hand position on the levers), rather than the machine's geometry, enables the LFC drivetrain to be composed of a lightweight, single gear ratio chain drive made from bicycle components that cost less than \$20 USD and are found anywhere in the developing world [9]. The LFC drivetrain provides a 3:1 change in mechanical advantage; to put this performance/cost ratio into perspective, Shimano XTR mountain bike components, the company's top model, provide a 6:1 change in mechanical advantage but cost more than \$1500 USD [10, 11]. The overall cost of the LFC when produced in India and shipped anywhere in the world will be approximately \$150 USD. This price point is equivalent to that of the most commonly distributed wheelchairs in developing countries [12] and is 30 to 40 times less expensive than other off-road wheelchairs with similar capabilities [13, 14]. For indoor use, the levers on the LFC can be removed and stowed in the frame, which converts the chair to a regular, pushrim-propelled wheelchair.

This paper presents the evolution and validation of the LFC design through three user trials in East Africa, Guatemala, and India. The LFC project is an example of stakeholder-driven design, in that our partners in developing countries did not simply articulate their needs; they participated in the entire design process to identify and create solutions as well. Survey data and interviews from test subjects were used to identify strengths, weaknesses, and ideas for revision of the LFC, as well as show its improvement in performance on various terrains after succes-



FIGURE 1. The Leveraged Freedom Chair (LFC). A) Perspective view of a Guatemalan trial subject in the LFC. B) LFC variable mechanical advantage, single speed drivetrain. All components in the drivetrain are made from bicycle parts found anywhere in the developing world. Inset gives the mathematical relationship for how the ratio between LFC speed (V_{Chair}) and pushing speed on the levers (V_{Hand}) varies as a function of the effective lever length (L), which is determined by hand position on the levers. Other labels: diameter of the chainring (D_{CR}), diameter of the freewheel (D_{FW}), and rear wheel radius (R_W).

sive iterations of the design. Biomechanical data demonstrate the LFC's superior performance to conventional wheelchairs in speed, efficiency, and propulsion force. Our trials included subjects who use a variety of mobility aids, including hospital-styled wheelchairs, high-end, lightweight western-styled wheelchairs, and hand-powered tricycles. Since the LFC is designed to provide mobility to those who need the seating and postural support of a wheelchair, and because hospital-styled wheelchairs are the most commonly distributed wheelchairs in the developing

world [12], the results presented in this paper compare the performance of the LFC to conventional, hospital-style, pushrim-propelled wheelchairs, unless otherwise noted. Hand-powered tricycles are not included in this paper because they cannot be used indoors.

MATERIALS AND METHODS

User Trials of the LFC

Each trial was conducted in partnership with a local developing country wheelchair manufacturer/distributor. Clients of these organizations, who are users of conventional wheelchairs or hand-powered tricycles, were asked to participate in the trials. Each trial subject was required to have a working mobility aid to use in the event that the LFC became inoperable, unsafe, or uncomfortable. Subjects participated in the trials at their own free will and were encouraged to use the LFC as much as possible but were not required to meet a usage quota. Each was allowed to keep their LFC, free-of-charge, at the end of the trial. All trials were approved by MIT's institutional review board as well as those of the respective local partner organizations.

All of the trials followed a similar format, wherein each subject was given an LFC to use for an extended period of time. At the culmination of the trial, subjects underwent biomechanical testing and were surveyed to provide input on strengths and weaknesses of the LFC design, as well as brainstorm possible upgrades. An important facet of conducting these interviews was establishing a good rapport and mutual respect with the subjects; each was told that he or she had invaluable knowledge about what it is like to be a mobility aid user in the developing world and that this knowledge was critical to ensuring that the LFC became a viable and successful product. We stressed that combining our knowledge – considering engineering, manufacturing, distribution, economic, social, and usage factors – we could create something together that none of us could alone. Appreciating the value of all participants' roles in the project, independent of citizenship and educational level, was critical in acquiring honest feedback and encouraging the trial subjects to articulate design solutions, as well as requirements and constraints.

The surveys administered to all of the trial subjects included rating the performance of their current mobility aid and the LFC on various terrains using a 1-5 scale, with 1 very bad and 5 very good. The terrains included: indoors, pavement, long distances on flat terrain, footpaths, hills, muddy and sandy soil, and extremely rough and uneven terrain.

Specific details of the trials in each country are described in the following paragraphs.

East Africa Trial. Six LFC prototypes were produced with our partner, the Association for the Physically Disabled of Kenya in Nairobi. One chair was tested in Tanzania, one in

Uganda, and the remaining four in Kenya. Members from our team trained the subjects how to use the LFC. The trial ran from August 2009 to January 2010. Three of the subjects (2 women and 1 man) were active wheelchair users, in that they could propel themselves without assistance, one was a wheelchair user (woman) who needed assistance with propulsion, and two were fulltime hand-powered tricycle users (both men). This trial differed from the following two because each subject was surveyed about the performance of his or her existing mobility aid before the trial; surveys about the LFC were conducted after the trial. In subsequent trials, the subjects' current mobility aid and LFC were included in surveys at the end of the trial. Only data from the three active wheelchair users are included in this paper. Although two did not use hospital-style wheelchairs, they had used them in the past and their current wheelchairs were pushrim-propelled. Biomechanical data, of the quality and comprehensiveness as those acquired in the following trials, were not collected for the East Africa subjects and are thus not included in this paper.

Guatemala Trial. Twelve LFC prototypes, upgraded from the East African design, were produced with our partner, the Transitions Foundation of Guatemala in Antigua. They were given to twelve active wheelchair users. The trial ran from November 2010 to January 2011. Five of the subjects were Transitions staff (all men) who compared the LFC to a hospital-style wheelchair in the trial. The remaining seven subjects were clients of the Foundation (3 women and 4 men). The clients were not trained how to use the LFC when they received it; as such, their results are not included in this study because their proficiency using the LFC varied greatly and they were not able to fairly benchmark the LFC against their current wheelchairs. Biomechanical data were collected on an approximately one-kilometer long test course on a dirt road in Hato, Guatemala, a village outside of Antigua.

India Trial. Twenty five LFC prototypes, upgraded from the Guatemala design, were produced with Pinnacle Industries of Indore and distributed to patients throughout India through Bhagwan Mahaveer Viklang Sahayata Samiti (BMVSS), commonly known as Jaipur Foot. BMVSS was sought as a partner on the LFC project because it is the largest disability organization in the world in terms of assistive devices [15] and can scale the distribution of the chair once it goes into production. The trial ran from June 2011 to October 2011. Twelve of the subjects were active users of hospital-style wheelchairs (2 women and 10 men) and thirteen were hand-powered tricycle users (3 women and 10 men). Data from the tricycle users are excluded from this paper. After the trial, we were able to follow up with eight (1 woman, 7 men) of the wheelchair users, seven of whom underwent biomechanical testing (1 woman, 6 men) and whose data are included

in this paper. These tests were conducted throughout India, at the subjects' homes when possible, or on a terrain representative of the home environment when not possible. The remaining wheelchair users were not available for follow up because of illness, family commitments, or because they were unreachable on their mobile phone.

Biomechanical Testing

Each test subject who underwent biomechanical testing rode their conventional wheelchair and the LFC on terrain that was representative of their home environment and for a distance that was representative of a daily commute. Each device was ridden for the same distance, following the same path. The subjects chose the distance to travel and were requested to maintain a pace that would not require stopping for rest, although rest stops were permitted when required. When rest stops were taken, the time spent resting was included in the overall time of the test, which was used to calculate the average velocity results reported in this work.

In each test, subjects were instrumented with a data acquisition (DAQ) system that collects biomechanical data (Fig. 2). When attached to the LFC, the system measures forward/back and side/side pushing force on the levers, hand position on the levers, angular displacement of the levers, speed of the chair, inclination and side slope angle, heart rate, and oxygen consumption rate (VO₂). VO₂ is commonly used to measure physical exertion during wheelchair tests [16, 17]. When attached to a wheelchair, the system measures speed of the chair, inclination and side slope angle, heart rate, and oxygen consumption rate. Velocity and VO₂ are the parameters reported in this paper.

We designed and built our own DAQ system because of the harsh conditions experienced during testing in developing countries, and because an off-the-shelf, portable system would cost approximately \$10,000 USD [18]. Our DAQ box is based on two 10 bit, 8 channel acquisition boards that record at 100 Hz [19]. The DAQ box is powered by a 12 V lead acid battery and contains the necessary electronics to condition incoming signals to the voltage range required by the acquisition boards. Noise is removed from the data using the smooth function in Matlab [20] with a 21 point moving average, which yields an effective sampling rate of 4.76 Hz.

Velocity is measured by counting rotations in time of the rear wheel of the wheelchair/LFC and knowing the wheel's diameter. A magnet attached to the wheel passes by a reed switch attached to the chair's frame, which sends a signal to the DAQ for each revolution. This setup is akin to that used on many bicycle trip computers.

Oxygen consumption is measured through a custom made VO₂ mask (Fig. 2). The system is based on a mask from a constant positive airway pressure system, used to treat sleep apnea. All vents in the mask are sealed and the main inlet/outlet tube



FIGURE 2. LFC trial subject in Guatemala wearing biomechanical testing equipment. The mask worn by the subject is connected to a spirometer and oxygen sensor, which measure oxygen consumption rate (VO₂).

feeds into a spirometer [21], which measures flow rate of the air breathed in and out, and an oxygen concentration sensor [22].

Each subject's maximum attainable propulsion force using the LFC and his or her conventional wheelchair was measured. This was accomplished by connecting a force scale between the wheelchair/LFC and an immobile object and having the subject produce the highest static pulling force possible with each device. The connection point on the chair was chosen to be as close to the ground as possible, to minimize moments placed on the chair frame that could tip the subject backwards. Tests of both chairs for each subject were always conducted on the same ground type for consistency in traction.

DESIGN EVOLUTION RESULTING FROM STAKEHOLDER FEEDBACK

Design Upgrades Identified and Implemented

Figure 3 shows the three iterations of the LFC design that were used in East Africa (Fig. 3A), Guatemala (Fig. 3B), and India (Fig. 3C). Major design changes that resulted from stakeholder feedback are denoted. All six subjects in the East Africa trial said that the LFC was too wide to fit through a standard doorway and that none of them used the chair indoors. This feedback made our team realize that the LFC had to be a viable conventional wheelchair when the levers are removed, as the levers would typically be used only for an hour or two per day during long distance travel. The second concern about the design, raised by five of the East African test subjects, was that the LFC

tipped backwards too easily and felt precarious when going up hills. The final problem, agreed on by the subjects and our team, was that the LFC was too heavy; at 30kg (65 lbs), it was at least 9.1 kg (20 lbs) heavier than other developing world wheelchairs on the market.

The Guatemala LFC (Fig. 3B) was designed to rectify the issues raised in the East African trial. The width of the chair was reduced by 8.9 cm (3.5 in), making it 68.6 cm (27 in wide), which is approximately 1.3 cm (0.5 in) narrower than a hospital chair of the same seat size. This was accomplished by tapering the seat (inset a, Fig. 3B), making it wide at the hips and narrower at the front to allow clearance for the levers. Putting jogs in the levers (inset b, Fig. 3B) enabled the drivetrain to be set closer to the frame, which narrowed the stance of the chair. Finally, 4.4 cm (1.75 in) wide tires replaced the 6.4 cm (2.5 in) wide mountain bike tires that were used on the East African chair.

Backwards tipping stability was improved on the Guatemala LFC by lowering the center of gravity by 12.7 cm (5 in) compared to the East African version; 10.2 cm (4 in) resulted from a change in frame geometry and the additional 2.5 cm (1 in) was gained from switching to 24 in rather than 26 in wheels. A back pad (box c, Fig. 3B) was also added to help tipping stability. This pad acts like a bench press bench; it provides a reaction force against the user's spinal column when he or she pushes on the levers. In the East Africa LFC, users' upper torso would bend backwards over the top of the seat and shift their center of gravity backwards when the levers were pushed. The back pad keeps the spinal column straight and the center of gravity stationary.

The mass of the Guatemala LFC is 9.1 kg (20 lbs) lower than that of the East Africa chair. This was accomplished through changing the chain tensioning/seat adjustment system. The East Africa chair has heavy bolt plates to which the wheels affix. The Guatemala chair uses a lighter clamp system where the upper seat frame, which contains the lever pivots, clamps onto the lower frame, which contains the wheel bearings. Steel volume in the seat frame was also reduced by using 1.9 cm (0.75 in) rather than 2.5 cm (1 in) diameter tubing.

Following the development of the Guatemala LFC, Transitions experimented with adding straps to the chair to restrain movement of the rider's torso and feet. Many subjects in the trial, particularly those who had sustained a spinal injury, liked the security offered by the straps, particularly when going down hill and pulling on the levers to apply the brakes. Three of the twelve subjects requested that straps be standard in future versions of the chair. Five test subjects suggested that the parking brakes be moved to a new position. When using the pushrims, the parking brakes could pinch the rider's thumbs against the tires. The levers also tended to hit the parking brakes, limiting their stroke, when propelling the LFC at high speeds. The most common suggestion voiced in the Guatemala trial, which was made by six of the seven people whose results are excluded from this paper because they were not trained how to use the LFC, was that

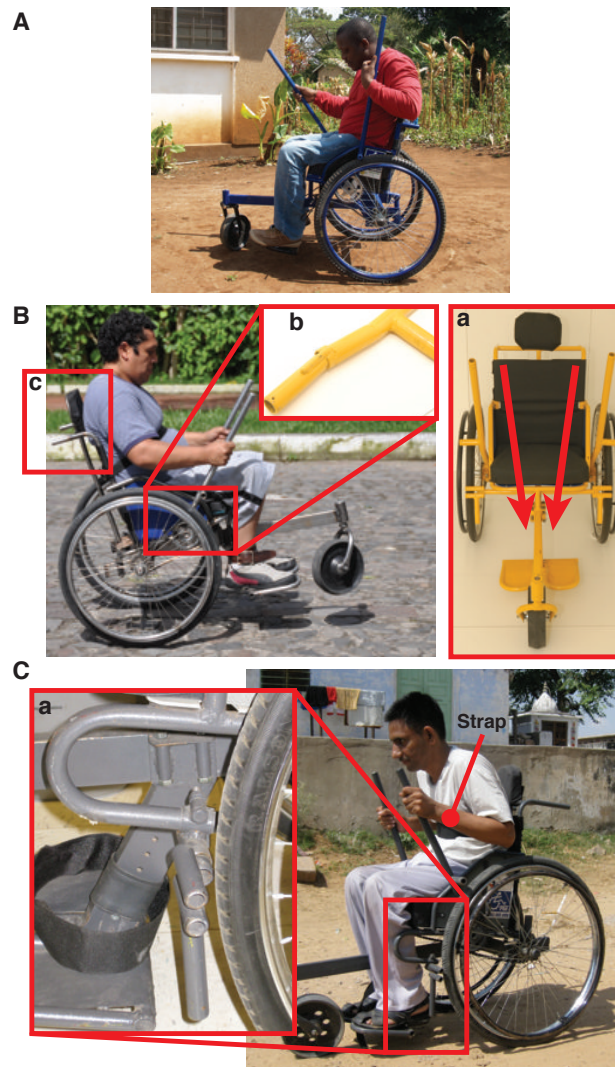


FIGURE 3. Major changes made to the LFC design through three user trials. A) Trial subject in East Africa. B) Trial subject in Guatemala. This version of the LFC was narrowed by 8.9 cm (3.5 in) compared to the East Africa version by tapering the arm rests to make the seat wider at the hips and narrower at the front (inset a, denoted by arrows), to allow swing clearance for the levers, and by jogging the ends of the levers to position the drivetrain closer to the seat frame (inset b). To prevent tipping backwards, the center of gravity of the LFC was lowered by 12.7 cm (5 in) and a pad was added to the seat back (box c) to maintain correct spinal posture and provide a reaction force when pushing on the levers. C) Trial subject in India. The parking brakes were lowered compared to those on the Guatemala LFC to increase the maximum angular swing of the levers (inset a). Chest, waist, and foot straps were added to improve security of the user (chest strap shown).

recipients of an LFC should be trained how to use it.

The India LFC (Fig. 3C) was designed to address the criti-

cal feedback voiced by subjects in the Guatemala trial. A chest, waist, and foot strap made of Velcro were added as standard features to the chair. The parking brakes were lowered by 12.7 cm (5 in) to allow for a larger stroke while still preventing the levers from hitting the ground (inset a, Fig. 3C). The new position of the parking brake mechanism is outside the hand stroke path when using the pushrims, which mitigates the risk of catching the user's thumbs between the brakes and the tires. A training program was implemented when the India LFCs were distributed. Each subject received more than two hours of instruction, including skills to cope with obstacles, before he or she brought the chair home.

The most common feedback following the India trial, voiced by seven of the subjects, was that the LFC should have cargo space either under or behind the seat. Storage bags will be incorporated into the production version of the chair.

Measuring Efficacy of Design Upgrades

Figure 4 shows aggregated survey data from the three trials comparing the performance of the LFC to conventional wheelchairs in different terrains. In the East Africa Trial (Fig. 4A), the LFC's deficiencies indoors, and advantages on rough terrain, are apparent. The low indoor score is consistent with feedback about the chair's width preventing it from being used indoors.

In the Guatemala trial (Fig. 4B), the LFC's reduced width compared to the East Africa chair resulted in a significantly higher score for indoor mobility, while still maintaining an advantage on outdoor terrain.

Feedback gathered after the India trial is the most compelling of the three. Figure 4C shows that the LFC provides drastically better performance on rough terrains compared to a conventional wheelchair with little to no compromise in indoor mobility.

RESULTS OF BIOMECHANICAL TESTS

Results from the Guatemala and India trial showing velocity and efficiency when traveling on a representative daily commute using both the LFC and a conventional wheelchair are given in Fig. 5. Distances traveled have been nondimensionalized by total distance of the test, which allows all tests to be plotted on the same scale, regardless of overall length. Efficiency is reported as velocity divided by VO_2 , which is a benefit/cost ratio in that high speed at a low metabolic cost is desirable. Note that the data are reported as a function of position along the course, not as a function of time. This is to show how both devices perform when traveling over the same terrain.

These data show that the LFC provides a significant performance advantage over a conventional, hospital-style wheelchair when traveling on developing country terrain. In true average

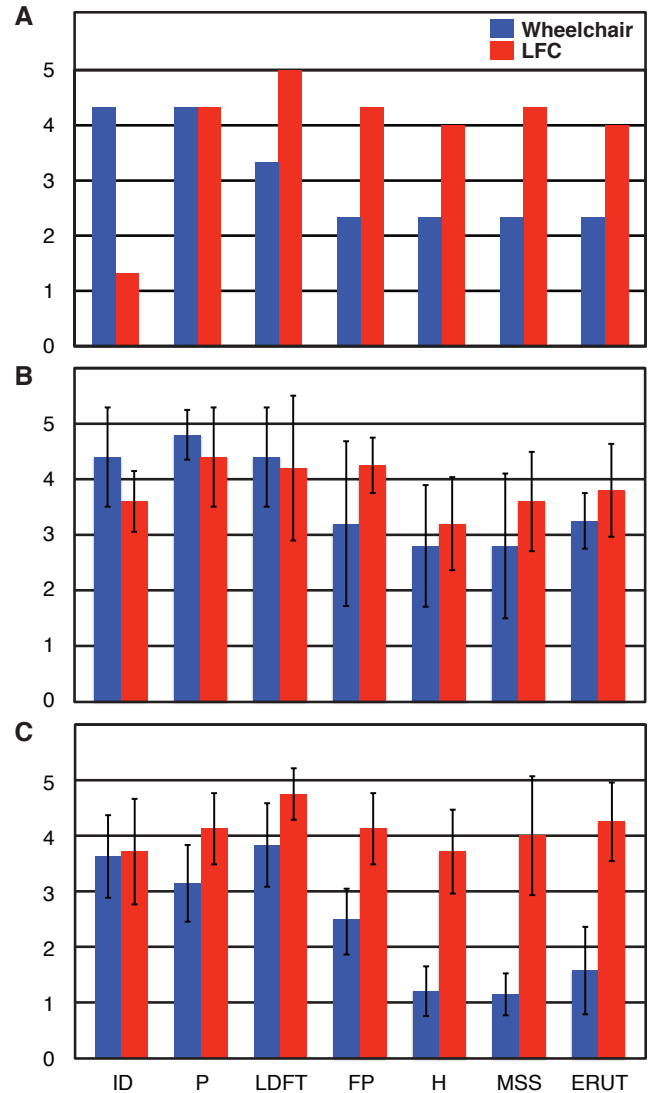


FIGURE 4. Subject-averaged survey data about the the LFC's performance on various terrains from three trials. A) East Africa trial (n = 3). B) Guatemala trial (n = 5). C) India trial (n = 7). Subjects rated the performance of their conventional wheelchair and the LFC on a 1 to 5 scale, with 1 being very bad to 5 being very good. Error bars denote \pm s.d. Labels: indoors (ID), pavement (P), long distance on flat terrain (LDFT), footpaths (FP), hills (H), muddy and sandy soil (MSS), and extremely rough and uneven terrain (ERUT). These data demonstrate how the evolution of the LFC design resulted in improved indoor performance and superior rough terrain performance compared to a conventional wheelchair.

velocity, determined by total distance traveled and total time of each test, the mean velocity of the LFC in Guatemala was $1.14 \text{ m/s} \pm 0.19 \text{ m/s}$, with the wheelchair averaging $0.63 \pm 0.14 \text{ m/s}$ (mean \pm s.d.). In India, the LFC averaged $0.91 \pm 0.18 \text{ m/s}$; the

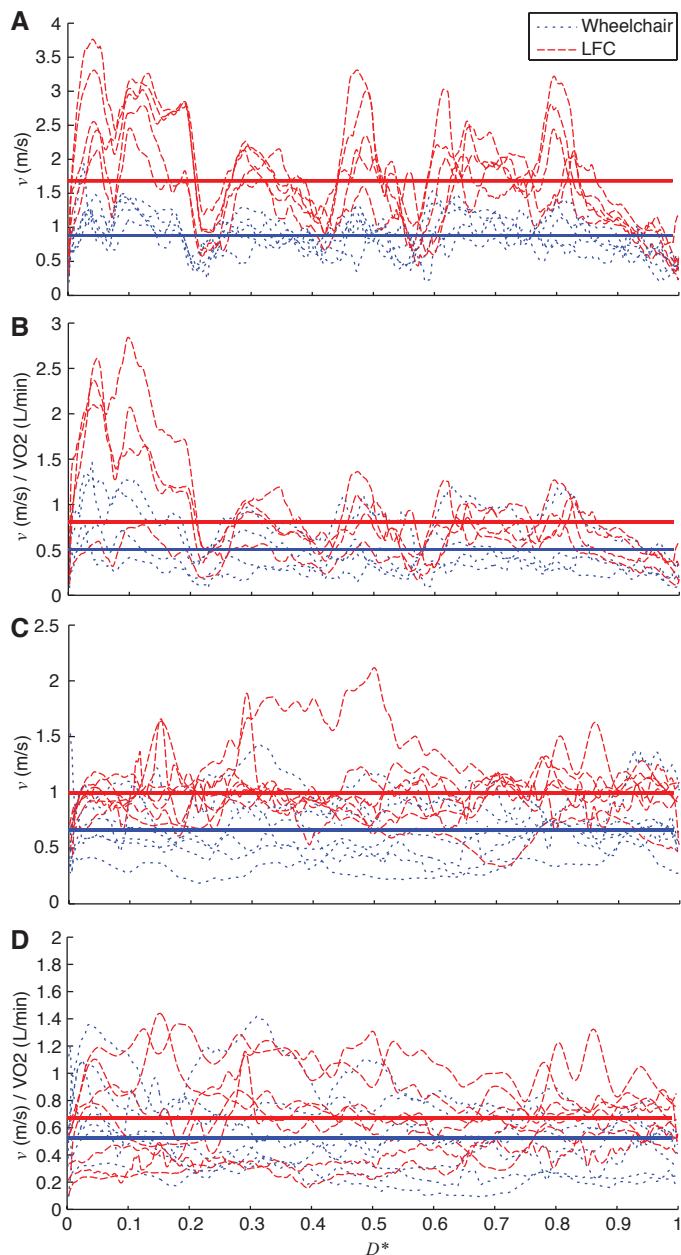


FIGURE 5. Biomechanical data comparing LFC performance to that of conventional wheelchairs. A) Velocity data for Guatemala ($n = 5$). B) Efficiency data for Guatemala ($n = 4$; VO_2 data was not recorded for one subject). D) and E) Velocity and efficiency data for India ($n = 7$), respectively. Solid lines denote average values for all subjects in the trial, calculated as a function of position along the test course. Efficiency is defined as a benefit/cost ratio, $\frac{v}{VO_2}$, as high velocity (v) for a low metabolic cost (VO_2) is desirable. Data are plotted versus non dimensional distance, $D^* = \frac{\text{distance traveled}}{\text{total distance}}$, as to normalize all test lengths, independent of actual distance.

wheelchair averaged 0.60 ± 0.23 m/s (mean \pm s.d.). Overall, the LFC provided the subjects with an average increase in velocity of 76 percent compared to the conventional wheelchair.

The LFC tested 59 percent more efficient than the wheelchair in Guatemala (Fig. 5B) and 28 percent more efficient in India (Fig. 5D). The combined average increase in efficiency for both tests was 41 percent.

In the peak propulsion tests, the LFC was able to generate 565 ± 95 N with the wheelchair able to produce 383 ± 51 N (mean \pm s.d.). In India, the measurements were 461 ± 84 N for the LFC and 301 ± 39 N (mean \pm s.d.) for the wheelchair. Subjects' average increase in peak propulsion force using the LFC instead of a conventional wheelchair, calculated over both tests, was 51 percent.

CONCLUSIONS

The biomechanical data presented in this paper demonstrate the effectiveness of the LFC variable mechanical advantage drivetrain. The LFC consistently and conclusively out-performed conventional hospital-style wheelchairs in speed, efficiency, and propulsion force in both the Guatemala and India trials.

Using stakeholder input to drive the evolution of the LFC resulted in improved performance with each iteration of the design. The upgrades shown in Fig. 3 were reflected in the positive changes in survey feedback in subsequent trials (Fig. 4), with the India LFC offering comparable indoor performance to a conventional wheelchair with far superior outdoor capabilities. Furthermore, the number and complexity of requested design revisions decreased with every trial; the relatively minor requests for upgrades following the India trial indicated that the LFC design was sound and ready for commercialization.

At the time of writing this paper, Pinnacle Industries, our production partner in India, was creating the tooling to produce 500 LFCs/month. BMVSS is scheduled to take delivery of the first 100 production-level LFCs in June 2012. Transitions have incorporated the LFC into their product line.

The LFC would not have come to fruition without the participation of stakeholders in the design process. These wheelchair users defined the requirements that led to the conceptualization of the chair, but also worked with our team to generate upgrades to continually improve the LFC through successive trials. When creating technology for developing countries and emerging markets, engineers must recognize stakeholders as collaborators and give them the opportunity to articulate problems and solutions.

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