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PRODUCTS AND DEVICES

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Design and development of mobility equipment for persons with disabilities in low-resource and tropical settings: bamboo wheelchairs

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ABSTRACT

Purpose: For persons with disabilities in low-resource and tropical settings, barriers to mobility and physical activity are steep. The aim of this study was to develop and test two low-cost, durable, sustainable, purpose-built wheelchair prototypes to support wheelchair users in low-resource and tropical settings. These bamboo wheelchairs, nicknamed African Chairs by Ghanaian daily manual wheelchair users who tested the devices, adopt two designs: an urban-targeted and a rural-targeted design.

Materials and methods: The rural-targeted design incorporated stability as its key design property for the purpose of navigating variable terrain. The urban-targeted design adopted a sleeker, more portable profile for environments that require wheelchair transport in vehicles and the navigation of elevators and ramps. Both designs integrated bamboo-rod skeletons, bonded by hot-glue gun, jointed and wrapped with epoxy-soaked fibers, then upholstered by a local tailor, with basic standard wheel components. An iterative design process incorporated expert consultation as well as user feedback.

Results and conclusions: The final prototypes received positive testing reviews from daily manual wheelchair users in Ghana. These locally-built, safe, economical bamboo wheelchairs have the potential to improve accessibility, provide more independence and reduce immobility-related health risks for many.

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Assistive technology device; mobility; indigenous wheelchair; bamboo; persons with disabilities; low-resource country

➤ **IMPLICATIONS FOR REHABILITATION**

- Persons with disabilities have a right to mobility, maximum independence, and the psychological, emotional, and physical health benefits of physical activity those rights confer.
- For persons with disabilities in low-resource settings, barriers to mobility and physical activity are steep, due to social stigmatization and the cost and adaptability of equipment.
- Bamboo wheelchairs have the potential to increase access to mobility and physical activity by allowing wheelchairs to be efficiently produced at cost, according to the user's needs.
- The aesthetics of bamboo wheelchairs can help reduce social stigma by avoiding the "medicalization" of wheelchairs and other traditional mobility devices.

Introduction

Immobility-associated health risks in low-resource and tropical settings

The United Nations' Convention on the Rights of Persons with Disabilities (CRPD) stresses the importance of ensuring personal mobility with the greatest possible independence in persons with disabilities [1]. Despite this, of the 65 million individuals requiring wheelchairs worldwide, the provision is met for a mere 5–15% [2,3]. Mobility enables access to important social, health and recreational activities, including mobility, physical activity for health, and regular exercise [4]. In low-resource settings, mobility impairment carries particularly dire consequences and is correlated with increased poverty rates, social stigmatization and marginalization, as well as decreased access to health and education services [5]. In all settings, those with developmental, physical and/or cognitive impairment are at higher risk of progressive chronic health conditions such as heart disease, diabetes, osteoporosis, arthritis, and neuropathic and musculoskeletal pain, compared to non-disabled persons [6–9]. Individuals with mobility-related impairment also suffer from higher rates of social isolation, depression, and lower perceived quality of life [10,11]. In low-resource and tropical countries especially, where deeply rooted cultural stigma and shame often weaken and frustrate social inclusion efforts, the psychosocial impact of disability can be magnified [12].

Mobility as a preventive health strategy

Degree of mobility, which here is defined as the ability of an individual to use his or her extremities to walk, grasp or lift objects, determines the level of independence, social function and quality of life for persons with disabilities [13]. Mobility can be improved through aids such as walkers, prostheses, crutches and wheelchairs. Research in high-resource countries has established that assistive technology successfully enables participation in work and education, exercise and sport, and maintenance of health, to positive social effects [14–16]. Increased mobility correlates with

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increased physical activity and regular exercise, which is also related to improved quality of life in persons with disabilities [17,18]. Exercise and sport can be used as both preventive therapy and treatment for cardiometabolic disease in wheelchair users and is recommended by the World Health Organisation (WHO). Ordinary activities of daily living are usually not adequate to maintain cardiovascular fitness [7,19–21]. Exercise and participation in sport have also been shown to reduce rates of depression among athletes with disabilities in high-resource countries [10,22,23]. Adequate access to assistive technology confers similar benefits on individuals with disabilities in low-resource and tropical countries, which has been well established [14,24–28].

Barriers to mobility in low-resource and tropical settings

Common barriers to mobility in persons with disabilities include cost, access, stigmatization, durability/adaptability and affordability of equipment [29,30] (Table 1). These concerns are especially troubling to individuals in low-resource settings, where obstacles may be perceived to be insurmountable [31]. An estimated 80% of global persons with disabilities live in low- and middle-income countries but in these countries, access to materials and affordability of devices can severely limit options [32]. The terrain in these areas is also a consideration: current assistive technology devices are often not adaptable to uneven or unpaved ground [33]. Maintenance and repair are unique and important elements of a mobility device in low-resource settings: devices need to be easily maintained locally and without specific expertise, for practicality and on-going use in the environment [14].

It is important to recognize that the social construction of disability can also be a barrier to mobility for persons with disabilities. As society actively excludes persons with disabilities from mainstream experiences and functions due to cultural and attitudinal factors, the disablement process is amplified [12,34]. One can apply this knowledge to mobility device concept and design in myriad ways (e.g., through minimizing the "medicalization" of devices), thus directly addressing and helping to reverse social stigma surrounding disability [35].

Region-specific and socio-contextual challenges are brought into sharp detail through a case study in Ghana. The Ghana-based non-governmental organization (NGO), Go Get Dem Wheelchair Racing Club, seeks to improve the lives of disabled persons through sport but is hampered by lack of stable government support, little usable infrastructure in largely rural environments, and limited access to mobility and training equipment [36]. As with this NGO, financial costs remain one of the largest barriers to mobility *via* mobility-enabling equipment for persons with disabilities in resource-poor and tropical settings [14,37]. The market price for standard manual wheelchairs starts from around 270 USD [38,39]. In context, $270 is almost twice the average monthly per capita income for an adult citizen of Ghana, provided they have an income, which is less likely to be the case among Ghanaians with disabilities [37,38].

Context-appropriate mobility equipment may offer a solution

This paper describes the conception and design for manufacture of two devices which address the need for easily-maintained, durable, low-cost, environmentally-appropriate mobility equipment for persons with disabilities: an urban and a rural bamboo wheelchair. The rural wheelchair incorporated stability as its key design property for the purpose of navigating variable terrain. The urban wheelchair adopted a sleeker, more portable profile for environments that often require transport of wheelchairs in vehicles and navigating elevators and ramps. The concept for the bamboo wheelchairs was derived from observations and testimony, in lieu of market data, which is not available in this region, from the many wheelchair users in Ghana who obtain second-hand standard metal chairs, either donated or purchased. Such chairs are not adjusted to the needs of these end-users, often because new or custom chairs are prohibitively expensive, do not withstand rough terrain, and may be difficult to repair locally. These devices have the potential to empower thousands of disabled individuals to improve their health, social, and emotional well-being [12,37].

Materials and methods

Price analysis

A market price analysis was performed to gain further understanding of how the bamboo wheelchair fits in the market. To our knowledge, no information on this topic is available from published literature, thus a price analysis was conducted through interviewing wheelchair users and shop owners in the two largest urban cities of Ghana, Kumasi and Accra. These are the main areas where Ghanaians can go to buy or sell wheelchairs. It is estimated that a conventional manual wheelchair has an average cost of 450–500 Ghana Cedi's (GHC) when purchased new. In 2017, the gross national income (GNI) per capita in Ghana was estimated to be 1880 U.S. dollars (e.g., 10,225 GHC), roughly a thirtieth of the USA's GNI per capita [40]. A standard manual wheelchair in Ghana, therefore, costs roughly half of an average Ghanaian's monthly income; this does not consider the 24.2% of Ghanaians who fall below the poverty line [41].

Design requirements

As defined by the WHO Wheelchair guidelines, one of the requirements to function as an appropriate wheelchair is that it meets the user's needs and environmental conditions [42]. User's needs can be met through local production processes that allow individual measurements, abilities, and specific requirements to drive fabrication. In the current study, two types of environmental conditions were considered in designing bamboo wheelchairs: rural (e.g., rough) terrain and urban (e.g., paved) terrain.

Table 1. Common barriers and facilitators to mobility for persons with disabilities in low resource and tropical settings.

Barriers	Facilitators
Psycho-motivational: psychological or emotional barriers that prevent mobility and community participation; including attitudinal barriers	Peer support, facility orientations, rehabilitation professionals
Built or environmental: barriers relating to the physical environment	Ramps, mats to even terrain, door assists, non-slip mats, rails, durable equipment
Cost/economic: ability to afford the cost of assistive devices, as well as maintenance and repair	Measures to increase economic power of persons with disabilities, donations, low-cost equipment
Equipment: availability of specialty / end-user adjusted and impairment-specific assistive devices	More adaptive assistive devices, modifications (such as Velcro straps) to existing devices, easy repair, local materials

Design process

Designers collaborated with a local non-governmental organization (NGO), which provided a workspace typically used for building bamboo bicycles [43]. Initial phases of the project consisted of interaction with local manual wheelchair users, retailers, bamboo bicycle builders and online research, to gain a thorough understanding of the design specifications. Simplicity, affordability, functionality and durability were found to be the most important design features.

Next, several prototypes were developed through an unstructured design process in collaboration with local experts in the field of bamboo. Local materials and skills were used as much as possible to minimize costs. For all prototypes, bamboo was used to construct the wheelchair frame, and Hemp fiber and epoxy were used to connect the bamboo after initial attachment with a hot glue gun. The wheels, bearings, axles, and receivers were standard, available metal components. The wheelchair designs evolved from hand-drawn sketches. A first-order structural fine element analysis (FEA) was performed to identify specific locations on the design that needed reinforcement (Figure 1). Exact values for the strength of the design could not be obtained since the software does not offer FEA of non-homogenous materials such as bamboo. Thus, the FEA was a geometric study that confirmed where the design team would need to reinforce the bamboo members. For this natural material, its properties are inconsistent as they depend on aspects such as type, age, moisture content, location of plantation, and time of harvesting. Additionally, material properties vary throughout one bamboo rod due to a varying inner and outer diameter along its length. However, the formula for maximum bending stress of hollow rods was used to estimate the relative bending strength of the bamboo rods. These values were used to determine their position in the design; stronger rods were placed on those locations experiencing higher stress. It was also taken into consideration that the nodes form the weakest points of a bamboo rod [44]. Therefore, the nodes were strategically placed; either at low-stress locations or at the joints to be covered in extra fiber and epoxy.

Manufacturing process

The manufacturing process is comparable to each of the wheelchairs. The *Bambusa vulgaris* bamboo species were used; planted, harvested and treated following the same procedure as for the bamboo bicycles by the Ghana Bamboo Bikes Initiative [43]. This bamboo treatment includes prevention of damage caused by pests. Bamboo rods were selected, measured, and cut based on their inner and outer diameter, indicating maximum bending stress. A skeleton of the wheelchair frame was then temporarily constructed using Epoxy Steel® and a conventional hot glue gun, (Figure 2). Next, the joints were permanently wrapped, using epoxy-soaked fibres. Those joints experiencing greater loads received an extra layer of epoxy-soaked fibres, providing additional strength. Finally, after the joints were sanded down and the skin was taken off the bamboo rods, the frame was sprayed with a waterproof protective layer.

Design I: rural wheelchair

For wheelchairs that are primarily used in rough outdoor environments in low-resource settings, stability is a key characteristic of these designs. Therefore, a rigid three-wheel design was chosen,

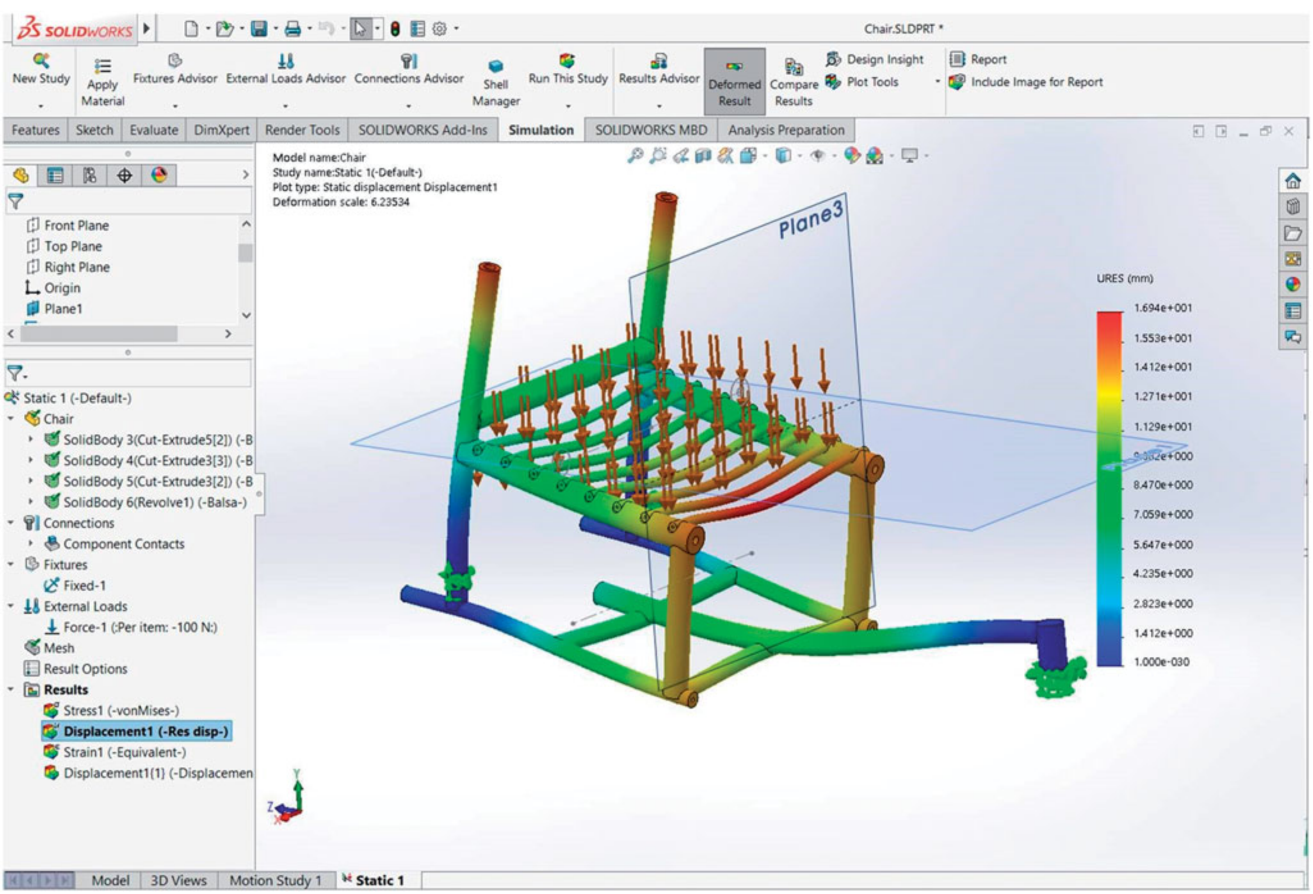

Figure 1. Drawing from SolidWorks®. Stress analysis performed on conceptual design to consider the weakest points.

Figure 2. The skeleton of the rural wheelchair constructed with *Bambusa vulgaris* bamboo, Epoxy Steel® and a conventional hot glue gun. Image © Marjelle F Scheffers.

Figure 3. Rural wheelchair prototype design aiming to support wheelchair users in low-resource and tropical settings. Image © Marjelle F Scheffers.

inspired by the wheelchair developed by Motivation, The Rough Terrain [45]. This design allows for an exactly constrained model, with three degrees of freedom [46]. Hence, it is more stable and feels more comfortable for the (new) user compared to the four-wheel design. Additionally, the front wheel has a relatively large diameter of 20 cm (7.9″) compared to regular front wheels. This provides less rolling resistance, making it easier to use on rough terrain. A longer wheelbase also makes propulsion on rough terrains easier as it reduces weight on the front castors [47]. A rigid design, rather than foldable, was chosen as simplicity and safety are valued over portability. The seat height is slightly lower than the average adult wheelchair, 46 cm compared to 49 cm, to increase stability by creating a lower tipping angle contributing to its safety [47]. The seat size was based on the regular size, low-cost Universal Slung Seat Pressure Relief Cushion developed by Motivation, which is 40 × 45 cm (16″×18″, width x depth), to potentially fit this wheelchair [48].The seat and cushion seen on the prototype were made by a local tailor from the Kumasi Technical Institute (KTI), using leather and foam from the local market (Figure 3). The base of the seat consists of bamboo rods on which the cushion is placed (Figure 2). The first and last rod is incorporated in the joints on their respective corners. The other rods are resting in grooves, created on the rods on the side, to prevent them from sliding back and forth. The (mud) guards prevent them from sliding laterally. Additionally, the bodyweight of the user will keep them in place. Based on user feedback, the seat was positioned at a slight backward angle to provide additional stability. Regular 61 cm (24″) Ø rear wheels were used with standard axles, that were later replaced with quick-release axles to increase the portability of the design. The receiver for these axles was locally designed and made in a mechanical shop.

Figure 4. Urban wheelchair prototype design in use for testing and aiming to support wheelchair users in low-resource and tropical settings. Image © Marjelle F Scheffers.

Design II: urban wheelchair

The urban wheelchair was designed based on the daily wheelchair of Raphael Botsyo, a three-time Paralympian for Ghana. His daily wheelchair is a custom made, four-wheel, rigid Quickie wheelchair [49]. The design of his wheelchair was modified to accommodate the mechanical properties of bamboo, namely its high compressive strength [44]. One of the adjustments made is the means by which the two rear wheels are connected. On Botsyo's wheelchair these were connected through a horizontal bar, with the rear wheels attached at both ends of this rod with quick-release axles. However, in this design the wheels are attached using a cross-like structure (figure 4). This wheelchair displays no features of adjustability to maintain simplicity; it was custom made to the measurements of Botsyo. The wheelchair has a sling seat, made of natural leather, rather than a rigid seat. This seat can easily be (de)attached with Velcro® straps on the back and underneath the seat which allows for easy cleaning and maintenance. Padding was added to the backrest and seat to provide comfort. A cushion can be placed on top of the seat for additional comfort. The backrest of this seat is low, stimulating the user to have an active posture when in the wheelchair, and the wheelchair is therefore applicable for users with upper-body mobility and strength. Regular 66 cm Ø (26″) rear wheels were used with standard axles and the front wheels of 13 cm Ø (5.1″).

Testing

The wheelchair prototypes underwent an iterative design process incorporating periodic testing. The design team gained feedback through the end-users and wheelchair designers and manufacturers. The rural wheelchair prototype was tested by five players from The Greater Accra Wheelchair Basketball team. This testing happened through interaction with the players, in an informal interview-like style. Suggestions made by the players, experienced wheelchair users, were applied to the next prototypes. Additionally, the team gained feedback from a Dutch wheelchair expert center, Double Performance, on the design of the urban wheelchair prototype, contributing to further improvement [50].

Results

User feedback

Feedback from the end-users was important for two main reasons. First, it helped in understanding how the concept of a wheelchair made of bamboo was received – if the aesthetics of such a wheelchair appealed to the end-users. Second, their feedback lead to technical adjustments of the design to improve functionality.

The chairs performed strongly when tested by Ghanaian wheelchair users, who additionally commented on the "African" nature of the bamboo frames and their aesthetic agreement with the local environment. The medicalized metal chairs common in this population, in turn, medicalize the users: with the familiar bamboo-frame prototype, users could feel that ostracization breaking down. One user commented had she the daily choice between an "African chair" and her second-hand metal frame chair, she would choose the former every time. Several others mentioned they "would love to ride this chair." These end-user perspectives motivated continued concept development. Specific feedback on design and functionality lead to several adjustments. For example, rear-wheel height adjustability was incorporated by adding receivers at different vertical positions, allowing the rear wheel to connect to its quick-release axle *via* receivers at varying heights. The height of the backrest was increased to provide extra support for those with less upper body strength and neuromuscular control. Also, a thicker front wheel was used to make it easier and smoother to ride. End users also mentioned it was necessary to add a feature that enabled them to strap their legs to the chair to make sure their feet did not fall off. This feature has not been incorporated in the final prototype yet.

Manufacturer/designer feedback

The urban wheelchair was taken to a Dutch wheelchair expert centre, Double Performance [50]. They were impressed by how many relevant design features had already been incorporated in this first relatively simple concept of the bamboo wheelchair. Based on their feedback the design team made several adjustments to the design for further improvement. The centre of gravity was placed more posterior relative to the rear wheels to create an "easier feel" when riding it. The synthetic material of the seat was replaced by natural leather, and more padding was added to the backrest, allowing it to form to the natural shape of the user's spine, which is important for comfort [50]. Additionally, the placement of the receivers was adjusted for the axles of the rear wheels. A stronger attachment of the guards was also created, since the user often pushes off these guards to move him- or herself in and out of the wheelchair. Furthermore, it was confirmed that the use of spoke wheels was a good choice for this concept; although they break relatively easily compared to novel rear wheel designs, they are the cheapest option on the market and easy to repair when they break down, especially since they are very similar to bicycle wheels.

Discussion

Persons with disabilities have a right to mobility, to maximum independence, and to the psychological, emotional, and physical health benefits of physical activity those rights confer. The need for mobility-enabling assistive devices such as wheelchairs in low-resource and tropical settings is largely unmet. Where this need is met, devices are often ill-suited for the end user's socio-cultural and physical environment, increasing the risk of physical injury and equipment failure [14].

The rural and urban bamboo wheelchair prototypes meet the distinct identified requirements of assistive device design in low-resource and tropical environments. They can be produced for approximately 120 USD, source local and widely available materials, involve local craftspeople putting emphasis on sustainability and ease of repair, meet chief demands of portability in the urban setting and stability in the rural setting, and are adjustable to end-user needs in real-time, *via* local feedback-response communication. Social, financial, and environmental barriers should be examined and reported on in design and development literature; this will address the present need and provide the groundwork for improved research and development processes in the future.

This study has limitations. Namely, while the urban and rural bamboo wheelchair prototypes were received positively, more extensive user-feedback in a manner that allows for rapid iterative design is needed. Specifically, the user-feedback group should focus on a broader group of wheelchair users. The wheelchair basketball players that tested the prototypes are experienced and fit users, who do not represent the average person in need of a wheelchair.

In addition, several aspects of these initial prototypes have clear room for improvement. The drawback of the high-strength properties of epoxy is a large contribution to the total weight of the wheelchair, which negatively impacts manoeuvrability and transportability. Therefore, the relationship between the amount of epoxy necessary to meet durability and safety standards should be further examined to minimize use. More extensive testing needs to be performed to gain a better understanding of the durability, safety, and functional aspects of the design. Finally, the prototypes have only gone through initial testing for functionality. Considering quality issues are more common in low-cost devices, it is essential to demonstrate these aspects are addressed in the design, and further refined in the production process. For example, bamboo bicycle frames use jigs to precisely connect bamboo rods on a specific angle; a similar model could be adapted by wheelchair prototypes to ensure proper, safe and similar manufacturing techniques used in the construction of each device.

Ongoing testing and refinement of these devices and other bamboo wheelchairs offers an opportunity for interdisciplinary collaboration between wheelchair manufacturers, suppliers of wheelchair parts, physiotherapists, physiatrists and other experts. As this concept matures, it has the potential to contribute to the largely unmet mobility needs of wheelchair users in low-resource and tropical settings, which can ultimately improve the quality and duration of life in this cohort of persons with disabilities [13].

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