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Development of a dual-purpose wheelchair for COVID-19 paraplegic patients using nigerian anthropometry data

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Abstract

Due to the numerous numbers of COVID-19 infected patients, the call for more isolation centers and hospital facilities, the widespread of COVID-19 virus amidst the health caregivers as a result of the handling of infected patients and the challenging situations of the paraplegics, a dual-purpose wheelchair is thus proposed for isolation centers and hospitals in the underdeveloped countries. The dual-purpose wheelchair was developed to facilitate sitting and sleeping postures that are desirable in handling the challenges of COVID-19 paraplegic patients in homes, hospitals and rehabilitation centers. The documented anthropometry parameter of the 5th, 50th, 75th and 95th percentile distribution of Nigerian paraplegics were retrieved and used in the design. The developed wheelchair was powered by a battery that converts the system from the wheelchair mode (sitting mode) to the bed (sleeping/relaxation) mode or vice versa. The average conversion rate of the dual-purpose wheelchair from bed mode to sitting mode and sitting mode to bed mode at no load is about 149.7 s and 163.6 s respectively with a standard error of ±0.2 s. Also, the average conversion rate from sitting mode to bed/sleeping mode and bed mode to sitting mode under load is about 150.4 s and 166 s respectively. The ergonomic suitability and comfortability were determined from the computed average acceleration ($A_{\text{AVER}}$), vibration dose value (VDV), and weighted acceleration value ($A_{\text{WEIGHTED}}$). The result from the performance test shows that the average acceleration falls between the range of 0.10 m/s² and 0.29 m/s² and the vibration dose value (VDV) ranges between 0.01 m/s² and 1.35 m/s². The weighted acceleration ($A_{\text{WEIGHTED}}$) was also computed and found to be between the range of 0.01 m/s² and 0.35 m/s² vibration value. Thus, attesting that the dual-purpose wheelchair design is ergonomically correct and safe to be used. The cost of the production of the prototype is estimated at one hundred and ninety dollars (190 USD).

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Introduction/study background

Coronavirus disease 2019 acronym as COVID-19 was made known to be world pandemic by the World Health Organization in January 2020. The spread of this deadly disease became alarming at an exponential rate to the extent that the whole world is put in a state of comatose [1]. The spreading rate of the devastating effects of this virus activity on human calls for urgent attention in mitigating against it. As of 10th August 2020, COVID-19 which was first discovered in Wuhan, China in December 2019 now has more than 19,718,030 confirmed cases and 728,013 deaths recorded globally. Nigeria which had her first index case on 27th February 2020 is yet to reach its peak and now has 46,577 confirmed cases and 945 death recorded [2].

Fasanya and Dada [3] established that the hospital workplace violence which is as a result of patients’ dissatisfaction stemming from untimely attention, temporary neglect of patients, degraded or insufficient bed spaces and other health facilities, etc. have made the health care providers unsafe, vulnerable to harassment and infections from their patients. Thus, attention must be drawn to this in salvaging the challenges. Also, Chen and Zhao [4] posited that health officials or health care providers became the frontliners in the treatment and management of infected patients. Often, many of these workers put their lives on the line to ensure that patients receive the necessary care as deem fit. In the process of administering their services, knowingly or unknowingly, they are cut up with the infection due to incessant handling of patients and unsecured personal protective equipment (PPE).

Most oftentimes, the physically challenged are being neglected or forgotten as their incapability is being taken for granted. There are acts and policies in place to ensure that the physically challenged are given the best care they deserved under the health care delivery sector. However, most of these policies are not wholly delivering the best service to these groups of people. For instance, Ordway et al. [5] found out that the “Americans Disabilities Act” is ineffective to make a great change in the delivery of health services for the physically challenged. Also, the World Health Organization (WHO) [6] posited that the physically challenged would be affected by COVID-19 due to interruptions in the health care service delivery they depend on. And opined that the barrier could be reduced if stakeholders and researchers resolve to take a suitable approach. In line with this submission and the increasing number of paraplegics in Nigeria, there is a need to provide means of making them more comfortable coupled with proactive measures should any of them show signs of infections that will lead to being isolated. Based on the rising fear and challenges in the underdeveloped/developing nations, Ebenso and Otu [7] raised a question on the ability of Nigeria being able to curtail Covid-19 judging from the previous epidemic outbreak. It is worthy to note that the authors’ assessment hinges on the nation’s capacity to provide hospital facilities needed for isolation and quarantine should the transmission increase geometrically.

On a general note, there is a need to provide a means of making the paraplegics more comfortable by providing a system that can be used for different purposes such as relaxation, medical examination, mobility, and several activities performed by humans with no disability [8]. The importance of a wheelchair as a device is to improve locomotion and promote functional independence, allowing the user to perform his/her activities of daily living. In the past, bioengineering has successfully generated the proof for wheeled-technology on ergonomic design and fitting procedures, which has significantly contributed to this purpose [9]. Anthropometry is an aspect of ergonomics dealing with the measurement of human body dimensions and certain physical characteristics [10]. It is used as a guide for the determination of the product’s heights, clearance, grips, and reaches in the workplace and equipment [11].

A substantial number of wheelchairs have been developed by different researchers using different concepts. Ujawnwe and Mahalle [12] presented a mechanically operated wheelchair convertible stretcher and walker meant to eradicate and ease the process of transferring disabled patients from the wheelchair to hospital bed. Despite the goal of the design made, the patients’ or users’ ergonomics factors were not considered in the development of the convertible wheelchair. Morales et al. [9] worked on the Mechanical and kinematic design methodology of a new wheelchair with additional capabilities but the work was majorly on the climbing mechanism of a wheelchair without considering the anthropometry parameter of paraplegics in the design. Borkar et al. [13] presented a mechanically operated wheelchair in which the purpose was to design a wheelchair convertible stretcher which is boon to the medical field and designed to be operated easily either by the patient or by the medical attendant and to the comfort of the patient but the wheelchair is not automated in nature.

Rashid et al. [14] fabricated a pneumatically powered wheel chair-stretcher device for assisting caregivers in rendering services to disable patients with mobility challenges. These authors employed the use of a shock absorber system as the lifting mechanism, however, the wheelchair was customized or limited to patients whose weight was not more than 100 kg within the Indians’ anthropometric data range. In the same vein, Hirudkar et al. [15], developed customized automatic stretcher cum wheelchair for facilitating the mobility of disabled patients and as medical equipment in the hospitals using the Indians’ anthropometry for its design. Ehsanullah et al. [16] also worked on the synthesis of a trolley convertible wheelchair for patient handling to eliminate manual handling of patients which could cause injury to the patient due to stress or infect the medical caregiver(s). Ehsanullah et al. [16] gave the schematic design of the trolley cum wheelchair which was not automated and could not solve the problem faced by Nigerian paraplegics because the anthropometry data used is not Nigerian.

Inferentially, all the aforementioned authors’ works could not make use of anthropometry data of any country in Africa let alone Nigeria for their design. Authors such as Ayodeji and Adejuyigbe [17] and Ayodeji and Adeyeri [18] whose works
made use of Nigerians’ anthropometry data in solving part of the problems faced by Nigerian paraplegics only worked on the development of CAD software for wheelchair and tricycle design. Their research output was limited to designing a single purpose wheelchair and tricycle using anthropometry data but could not integrate sitting and mobility functions in the same module. Also, Ashiedu and Igboanugo [19] only worked on measurement and evaluation of anthropometric data of Nigerian adult paraplegics for wheelchair design but could not take the work further. The design and fabrication of an adaptive left throttling pedal for V-Boot wagon 230 for right leg paraplegic patients was developed by Ayodeji et al. [20]. However, information from this study is not relevant or sufficient to develop or improve a wheelchair. It is problem-oriented research and could only solve the problem for a paraplegic patient who has a problem with his right leg and still desires to drive his vehicle with ease, not for paraplegic having problems with his two-legs and who needed to use a wheelchair.

With the work of Oriola et al. [21] on the development of an anthropometric database for the paraplegic population in Nigeria, an indigenous design of wheelchair, equipment, workspace and facility for Nigerians could be developed. In view of this, the present work has harnessed these data to develop a dual-purpose wheelchair for the paraplegics in Nigeria. Thus, the research is contributing the prototyping of an indigenous 120 kg capacity dual purpose wheelchair using Nigerian anthropometry data that could serve the purpose of sitting, sleeping, and a temporary alternative for a hospital bed. This research has taken into consideration the cost of producing a dual-purpose wheelchair using locally available materials to reduce the production cost in prototyping the dual-purpose wheelchair that could be used in isolation centers as well as mobility for both sitting and sleeping. Section 2 of the manuscript discussed the materials and methods used for the achievement of the research aim. Section 3 analyzed the results derived while the conclusion is discussed in section 4.

Materials and methods

The anthropometry parameters [17,19,21] showing the 5th, 50th, 75th and 95th percentile that serve as anthropometry database for the adult Nigerian paraplegics (19 – 45 years) were retrieved and used for the design. The parameters were compared and used for the selection of dimensions for the various parts of the wheelchair. The developed wheelchair comprises the following units namely; backrest, the seat, leg rest, foot rest, headrest, armrest, rigid frame, the linkages frame, and the driving wheels. The wheelchair units were designed using standard dimension, relevant design equations and Nigerian paraplegic anthropometry parameters for both males and females.

The 3D modeling and assembling of the wheelchair were done using SolidWorks application software. Material selection for it was based on cost and the following mechanical properties: strength, wear resistance, toughness, rigidity, machinability, and ease of welding. The prototype of the wheelchair was then fabricated using locally available materials.

**Detailed design based on anthropometry data**

The Dual-Purpose wheelchair was designed using various design considerations. The design and development involve dimensions determination and analysis of parts, material selection, and ergonomics consideration. The design considerations made for the components parts of the wheelchair are as described in Table 1 [17,19,21], while the 3D model view and exploded view of the design concept are as shown in Figs. 1 and 2.
Simulation study of the designed dual-purpose wheelchair

The stainless steel base frame which serves as the major load support for the wheelchair was subjected to load analysis through simulation runs using Finite Element Analysis (FEA) under a maximum load of 1200 N as derived in Table 1 taking into account the properties of the material used in the design model. The outcomes of its stress, strain and static displacement analysis are as shown in Figs. 3–5 respectively. It can be seen that the maximum stress was pronounced at the joints in Fig. 3. Since the value of the maximum von Mises stress obtained by simulation is \(5.83 \times 10^6\) N/m\(^2\) too low when compared with the yield strength value of \((1.72 \times 10^8)\) N/m\(^2\) the stainless steel selected for fabrication, therefore the simulation of the fatigue is not necessary. The strain value of \(2.485 \times 10^{-5}\) is minimal in Fig. 4 as it is distributed in nearly every part of the design except where the frame parts and supports were connected. The distribution of displacement value of \(3.12 \times 10^{-2}\) mm in the design is high at the side of the wheelchair as shown in Fig. 5. Since the simulation results are in favor of the designed parameters, the fabrication of the wheelchair was therefore carried out accordingly as reported in subsequent sections.

Description and principle of operation

Fig. 6 shows the isometric view of the computer-aided design (CAD) model for the wheelchair and the developed dual-purpose wheelchair. The wheelchair frame was designed using a linkage mechanism to achieve the conversion of the wheelchair from sitting mode to sleeping or bed mode. Some of the accessories used are: 1.255 kg weight of electric motor with a rated stall torque of 19.99 Nm and unload high speed of 50 rpm; 12 V DC battery (75 AH); switches; 609.6 mm spoke wheels; flat plate material for leg rest; 350 kPa pneumatic tire with a diametric size of 609.6 mm; rolling contact bearings; 1000 kg capacity screw jack; and cushion materials. The wheelchair has two 609.6 mm spoke wheels and four 101.6 mm caster wheels. The two 609.6 mm spoke wheels have low density and low weight. The wheel could be coupled with treaded pneumatic tires to provide traction to enable the end-user to be able to use the wheelchair in different terrain. Hand rims which consist of a circular steel tube were attached to the driving wheels (609.6 mm) to permit control without soil ing the hands. Two out of the four 203.2 mm wheel casters were installed in the front part of the wheelchair and the remaining two were on the rear part of the wheelchair, this was done after the center of gravity have been calculated for proper balancing and comfortability of the end-user.

The fabricated dual-purpose wheelchair and its assembly were achieved through the implementation of detailed design with proper anthropometry dimension descriptions. The 5th, 50th, 75th, 95th percentile anthropometry parameters used for the design are as shown in Table 1. The conversion mode (sitting and sleeping mode) was achieved using a screw jack controlled by an electric motor connected to the linkage mechanism. The reciprocating motion needed for the conversion was activated and controlled by a switch. Due to the unavailability of some equipment and materials to be used, there was little variation in the material used in the design compared to the fabricated wheelchair.
**Performance evaluation on the developed wheelchair and results discussion**

The evaluation of the dual purpose wheelchair was carried out by critically examining the ease with which the chair would be converted from sitting mode to sleeping mode and vice versa and as well estimating its ergonomic suitability and comfortability for safe use. These two factors are as discussed in the subsequent subsections.

**Wheelchair convertibility evaluation**

The wheelchair was assembled and dismantled several times to determine the average assembling and dismantling time, the result shows that it takes 422 s and 394 s to assemble and dismantle it respectively. The result obtained for the con-
Fig. 4. Simulation output of static strain of the base frame of the designed dual-purpose wheelchair.

Fig. 5. Simulation output of static displacement of the base frame of the designed dual-purpose wheelchair.

Fig. 6. The isometric view of the designed and developed wheelchair.
Table 2
Conversion duration of the wheelchair (under no-load condition).

| Attempt | Bed Mode to Wheelchair mode t(s) | Wheelchair to bed mode time t(s) |
|---------|----------------------------------|---------------------------------|
| 1       | 150                              | 165                             |
| 2       | 149                              | 158                             |
| 3       | 150                              | 162                             |
| 4       | 149                              | 163                             |
| 5       | 150                              | 165                             |
| 6       | 149                              | 164                             |
| 7       | 151                              | 165                             |
| 8       | 150                              | 164                             |
| 9       | 149                              | 165                             |
| 10      | 150                              | 165                             |
| Mean    | 149.7                           | 163.6                           |
| Standard error | 0.21                  | 0.70                           |

Table 3
Conversion rate of the wheelchair (with load).

| Attempt | Mass(Kg) | Bed mode to wheelchair mode t(s) | Wheelchair to bed mode time t(s) |
|---------|----------|----------------------------------|---------------------------------|
| 1       | 95       | 152                              | 166                             |
| 2       | 65       | 152                              | 164                             |
| 3       | 70       | 152                              | 166                             |
| 4       | 98       | 151                              | 165                             |
| 5       | 62       | 152                              | 167                             |
| 6       | 80       | 152                              | 166                             |
| 7       | 75       | 151                              | 165                             |
| 8       | 63       | 153                              | 166                             |
| 9       | 83       | 142                              | 166                             |
| 10      | 56       | 151                              | 169                             |
| Average | 74.7     | 150.4                            | 166                             |

version time duration and mobility evaluation of the wheelchair at no-load and different loadings are as shown in Tables 2 and 3.

Table 2 shows the time taken to convert from wheelchair mode to bed mode under no-load condition. Observation shows that the average time taken to convert from bed mode to sitting mode is 149.7 s, while the time required to convert from wheelchair to bed mode is 163.6 s. It takes lesser time to convert from bed mode to sitting mode when compared to converting the same wheelchair from sitting mode to bed mode as much force is required to engage the conversion. The standard errors of ±0.21 and ±0.70 were established with the time usage in converting from bed to sitting mode and sitting to bed mode respectively. The posture of the user/operator at the point of engaging the wheelchair as well as inherent gliding from the joints adduce to the observed time variation in the conversion mode. Similarly, Table 3 shows the time taken to convert the wheelchair from sitting mode to bed mode under different loading conditions using ten (10) trials. It was observed that the average time taken to convert from bed mode to sitting mode is 150.4 s while the time required to convert from sitting mode to bed mode is 166 s. This corroborates the inference drawn from the observed data of Table 2, implying that more time is required to convert from sitting mode to bed mode as much work is required in carrying out the conversion.

Wheelchair ergonomic suitability and comfortability

The wheelchair ergonomic suitability and comfortability were determined using the Vibration Dose Value (VDV) and the Average RMS acceleration($A_{RMS}$) generated by the wheelchair when loaded. The determination of these indices is done by comparing exposure action and recommended limit values of the International Standard organization (ISO) 2631–1 (1997) and European Community directive 2002/44/EC with the perception threshold of Comfort Weighted Acceleration of (ISO 2631–1, 1997). The Health Guidance Caution Zone (HGCZ) was also adopted to validate the wheelchair suitability. And this is defined as the interval between the lower bound of 0.47 m/s² and upper bound of 0.93 m/s² in terms of an eight-hour energy equivalent acceleration [22]. While the wheelchair comfortability is validated using the recommended lower and upper VDV of 8.5 m/s¹.⁷⁵ and 17 m/s¹.⁷⁵ respectively [23].

Eq. (1) was used to evaluate the acceleration [16]

$$A_{RMS} = \left( \int_0^T a_w^4 (t)dt \right)^{1/2}$$

Where:

$A_{RMS}$ is the average acceleration at time t (m/s²)

$a_w$ is the acceleration at time t (m/s²)
Table 4
The vibration doses on wheelchair parts.

| Wheelchair parts | VDV (m/s^{1.75}) | A_{RMS} (m/s^2) |
|------------------|------------------|-----------------|
|                  | X    | Y    | Z    | X    | Y    | Z    |
| Headrest         | 1.51 | 0.02 | 0.52 | 0.25 | 0.11 | 0.15 |
| Backrest         | 1.32 | 0.01 | 2.26 | 0.12 | 0.13 | 0.25 |
| Seat             | 0.11 | 0.12 | 2.52 | 0.26 | 0.22 | 0.17 |
| Left armrest     | 0.01 | 0.06 | 2.47 | 0.10 | 0.20 | 0.25 |
| Right armrest    | 0.01 | 0.05 | 2.03 | 0.15 | 0.21 | 0.15 |
| Foot rest        | 1.79 | 0.01 | 2.35 | 0.24 | 0.29 | 0.25 |
| Leg rest         | 1.32 | 0.13 | 2.52 | 0.25 | 0.26 | 0.26 |

Fig. 7. Average RMS acceleration on parts of the wheelchair.

\[ VDV = \left( \int_0^T a_w(t) \, dt \right)^{1/4} \]  \tag{2}

Where:
- \( VDV \) is vibration dose value (m/s^{1.75})
- \( a_w(t) \) is acceleration at time (m/s^2)
- \( T \) is the period of exposure (seconds)

The weighted RMS acceleration was determined using the relationship in Eq. (3) and a weighting factor of 1 as recommended by ISO in all the axes.

\[ A_{\text{weighted}} = \sqrt{k_x^2A^2_x + k_y^2A^2_y + k_z^2A^2_z} \]  \tag{3}

Where:
- \( A_{\text{weighted}} \) is Weighted RMS Acceleration
- \( k_x, k_y, \) and \( k_z \) is the weighting factor on x, y, and z axes respectively.
- \( A_x, A_y, \) and \( A_z \) is average acceleration in x, y, and z axes respectively.

The vibration effect experiment was also carried out on the dual-purpose wheelchair by using an accelerometer to check the ergonomic suitability and comfortability as compared with the International Standard organization (ISO) standard. Table 4 shows the vibration dose and RMS acceleration values obtained for the wheelchair components as measured using an accelerometer. The maximum values obtained from each axis were compared with the International Standard Organization (ISO) standard and European Community (EC) Standard to determine the vibrations in the wheelchair as established by Council of the European Union (EU) [24] and Zhao and Schindler [25].

Fig. 7 shows the Average RMS Acceleration (A_{RMS}) of the wheelchair to be between 0.1 m/s^2 and 0.29 m/s^2. Comparing these values with the recommended Exposure Action Value (EAV) and Exposure Limit Value (ELV) of 0.47 m/s^2 and 0.93 m/s^2
respectively, it could be inferred that EC directive for daily exposure action value and daily exposure limit value (EAV) for both hand-arm and whole-body vibration acceleration value are still below the limit. The results of the VDV on the wheelchair are as presented in Fig. 8. The VDV which is the fourth-power value of the acceleration was used to evaluate the vibration dose from the wheelchair. The VDV exposure action and limit values are $8.5 \text{ m/s}^{1.75}$ and $17 \text{ m/s}^{1.75}$ respectively. Similarly, the EU directives values are $9.1 \text{ m/s}^{1.75}$ and $21 \text{ m/s}^{1.75}$. From this result findings, the vibration dose value obtained falls between $0.01 \text{ m/s}^{1.75}$ and $2.35 \text{ m/s}^{1.75}$ which is within the accepted limit, implying that the wheelchair is ergonomically suitable.

Fig. 9 shows the result of the weighted Acceleration RMS value ($A_{\text{weighted}}$). The result read from the accelerometer indicated that the headrest, backrest, seat, left and right armrest, footrest, and the leg rest have weighted acceleration values of 0.10, 0.15, 0.25, 0.20, 0.21, 0.25, and 0.15 respectively. None of these perception values are “a little uncomfortable” or “fairly uncomfortable”, “uncomfortable” “very uncomfortable” and “extremely uncomfortable”. They all fall to the perception of “not uncomfortable” as when compared with the perception threshold of comfort weighted acceleration by the International Standard Organization (ISO) and European Community (EC) Standards [23,26].
Conclusion

The dual-purpose wheelchair was designed, simulated, and animated with Computer-Aided Design software. The concept of FEAM in simulation study was employed to minimize materials wastage in the design. The prototype of the designed wheelchair was developed using locally sourced materials, and the selection of the material was based on availability, cost, and mechanical properties. The result shows that the average conversion rate of the dual-purpose wheelchair from wheelchair mode to bed mode and bed mode to wheelchair at no load is about 149.7 s and 163.6 s respectively. Also, the average conversion rate from wheelchair mode to bed mode and bed mode to a wheelchair when loaded is about 150.4 s and 166 s respectively. The ergonomic suitability and comfortability were determined from the computed average acceleration (ARMS), vibration dose value (VDV), and weighted acceleration value (AWRMS). The result from the experiment shows that the average acceleration falls between the range of 0.10 m/s² and 0.29 m/s² and the Vibration Dose Value (VDV) ranges between 0.01 m/s² and 1.35 m/s² which is below the recommended daily exposure action value (EAV) and daily exposure limit value (ELV) as compared with the standard. This result shows that the dual-purpose wheelchair is ergonomically suitable. The weighted acceleration (Aweighted) was also computed and found to be within the range of 0.01 m/s² and 0.35 m/s² vibration value.

The ease of handling in engaging and disengaging the wheelchair from chair mode to bed mode coupled with its comfortability and suitability has made it possible to be a good alternative to a hospital bed in an isolation center for COVID-19 patients as this will reduce the spread of infections from patients to the caregivers or health workers as it eliminates the transferring of paraplegics from the chair to the hospital bed. The estimated cost of production is one hundred and ninety dollars (190 USD), which is relatively cheaper compared with those imported being sold at three hundred dollars (300 USD) despite their non-conformance with Nigerians anthropometric design in providing the necessary comfort for the paraplegics. With the local content being promoted, when the wheelchair is mass-produced, the cost of producing a unit would be far lesser than one hundred and ninety dollars (190 USD), making it affordable by interested paraplegic. The design is very simple, easy to assemble and disassemble. This will make the cost of repair and maintenance to be very low. However, the standard error of ±0.2 s in the system response during conversion mode calls for further work on the choice of jack employed and the need for good workmanship in the production activities of the dual purpose wheelchair. In summary, the research has contributed the development of an indigenous 120 kg carrying capacity dual purpose wheelchair designed with Nigerian anthropometry data to the body of knowledge.

Declaration of Competing Interest

None.

Acknowledgement

The authors wish to declare that this research work has not received funding from any organization. However, the contributions of members from the Advanced Manufacturing and Ergonomic Research Team, the Federal University of Technology, Akure are acknowledged.

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