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# Mechanistic Modeling of Hydraulic Energy Transmission Technology of an Improved Dental Patient Chair Design

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**ABSTRACT:** This work focused on mechanistic modeling of hydraulic technology of an improved dental chair design. ISO 6385 standard for $P_{(M)}95$ patient were basis for system parameters, and fathom masses between 60kg-93kg, corresponding to DINED 2003 mass of patients, produced total load on the pantograph. The force exerted by the lower limb of the dentist is an ergonomic stressor that was experimentally studied using Pascal's law of the hydraulic system. Methodology adopted was mechanistic modeling technique. The results indicated that pedal force of 0.1375kN elevated trimmed chair (dead load) of 0.55kN, while pedal force of 211N to 277N were required to recline between 60kg-93kg masses on the system. It infers that the pump has a mechanical advantage of approximately 5, with displacement volume, 11.7825cm-2, that produced a platform displacement of 3. 75cm during a 15cm hydraulic pedal travel stroke. The experimental results corroborated Pascal's laws and is has technological significance on carrier-long musculoskeletal disorders (MSDs) of lower limb among dental practitioners.

**KEYWORDS:** Mechanistic modeling, hydraulic technology, Pascal's principle, dental chair, ergonomics, total load.

## INTRODUCTION

A dental unit chair is a generic device in dentistry, specially designed to support a patient's body that is undergoing dental for examination, diagnosis and treatment [1][2]. Essentially, it comprises of seat, head rest, back rest, arm rest, foot rest and pedestal, designed to discreetly recline, yet articulate, in part or wholly, in order to allow the patient to be placed into a prone position during treatment. Therefore, through articulation and recline, dental chair should support biologically- oriented posture of both patient and dentist in providing oral healthcare, more conveniently and efficiently within a reasonable length of time. But, developing appropriate mechanism to improve ergonomics has remained inefficient and costly, limiting access to oral healthcare. This has remained a subsisting challenge of office design in physical ergonomics. Engineering improvements in workstation and remodeling of equipment in dental operatory are most efficient and effective strategy of combating MSDs [3]. Manual operations, though appears technologically obsolete, but cannot be divorced in the context of solving societal problems of developing countries, such as Nigeria. Single working unit, considered a fundamental design concept of any patient support system, was adopted but remodeled with multi position articulation headrest and hydraulic technology, to manually but independently recline and articulate the dental patient chair for improve ergonomics and access. This paper aims at mechanistic modeling of hydraulic energy transmission technology of improved dental chair design.

## 1. Literature Survey of Dental Chair Design Requirements

Dental chair is ostensibly designed more for dental operator utility rather than comfort, creating a less pleasurable dental experience for patients and dentists [4]. In the context of dental chair design, [5] expounded the elements of chair-centric requirements of a working dental chair as building blocks of a successful dental chair to include: aesthetics, ergonomic, structural, technical and technological, medical and economic. Specifically, fundamental principle of ergonomics is to design work area and task around the professional/dentist, rather than compel the worker to adapt to poor design and task function [6], a principle that propelled Dr Naughton's design of dental chair.

Engineering psychology, purposefully, matches the design of systems to the limitations and capabilities of human users, to improve the relationship between people and machines by redesigning equipment, interactions or the environment. Medical device design primarily considers principles of work systems in relation to work tasks, sometimes requiring evaluation of services to medical devices or application of principles of human factor engineering for equipment evaluation. In this case, ergonomic stressors are involved in the study of interactions among humans and other elements of systems to optimize human well-being and overall system performance. In the existing literature, there was agreement on focusing on human factors, especially analysis of risk factors related to work equipment, work station design and human behaviour [7][8][9][10]. These were all encapsulated in ISO 6385[11] in Figure 2.5. Figure 2.5 shows ergonomic principles in design of work systems.

| | |
|---|---|
| Design in relation to anthropometrics | • Appropriate work height and reach; considered a single working unit; task design ensures that job is within physical and mental capabilities of workers; accomodation of user; sufficient space fo body movements; controls should be within functional reach; grips andhandles should suitthe structure of hand. |
| Design in relation to body posture | • Avoiding unnecessary/ excessive strain of tissues; alternate between sitting and standing; short chain of forces for high muscle of exertion; prolonged static muscular tension should not cause work fatigue. |
| Design in relation to muscular strength | • strength requirements should be within physiological desirable limits,; Mainteneance of prolonged static tension in the same muscle should be avioded. |
| Design in relation to body movement | • A good balance should be established among body movements; Motion should be preferred to prolonged immobility; Movements with accuracy requirements should not entail exertion of considerable muscular strength.; execution and sequencng of movements hould be facilitated by guiding devices. |
| Design of signal, displays and controls | • Controls should be designed and laid out in compactible mannerr with movementof the part of body operating it; Control movement, equipment response and display information should be mutually ompactible; controls shoud be laid out to ensure safe,unambigious and quick operations; criticalcontrols should be safeguarded against inadvertent operations. |
| Design of the work environment | • The work environment designed and maintained so that physical, chemical, biological conditions have no adverse effect on people. |

**Figure 1: Ergonomic Principles in the Design of Work Systems**

## 2. METHODOLOGY

One of the hallmarks of a model is to predict the future, whether empirical or scientific. Mechanistic models are, by nature, a scientifically based, simplified, but versatile description of how [12], in our case, hydraulic system can recline ergonomically. It is characterized by use of natural laws, sometimes expressed in complex equations, and with few data is capable of simulated, once validated. The basic approach to mechanistic modeling of systems involves building models based on the underlying physics and chemistry governing the behaviour of the process [12]. Mechanistic modelling relies on generation of novel hypotheses for casual mechanisms developed via observations of phenomenon of interest [13]. The causality of mechanistic model focuses on input-output relationships. Mechanistic models can indeed produce more realistic predictions and more can be done with it in terms of analyses. Mechanistic modeling relies on a two stage process: the first subset of available data is used for construction and calibration of the model, and subsequently, in a validation phase [13]. While mechanistic models are expensive in terms of human effort and expertise, it favour design processes. The development of mechanistic model follows workflow shown in Figure 2.

Mechanistic modeling of improved dental chair is based, initially on the anthropometric design considered DINED tables 2003 with anthropometric data for man and woman in Europe, abridged anthropometric reference data for children and adults in United States, 2007-2010 and kinesiology table of percentage of total body weight of $P_{(M)}$ 95 patients.

In this, the maximal length of the back of the patient chair for supporting shoulders on the side of top of the back, $P_{(M)}95$

$$L_{Back} = L_{srp-shouldr} - \{L_{not\ supported} - L_{middle\ of\ back\ suppt}\} \qquad (1)$$

Dimension Back support: As specified in Appendix E for $P_M(95)$ patient.

Dimension Arm rest: As specified in Appendix E for $P_M(95)$ patient

Length of seat

$$L_{seat} = L_{U.leg} + L_{part\ lying\ on\ seat} \qquad (2)$$

Length leg support

$$L_{leg\ support} = L_{part\ upper\ leg\ on\ leg\ support} + L_{lower\ leg} + shoe \qquad (3)$$

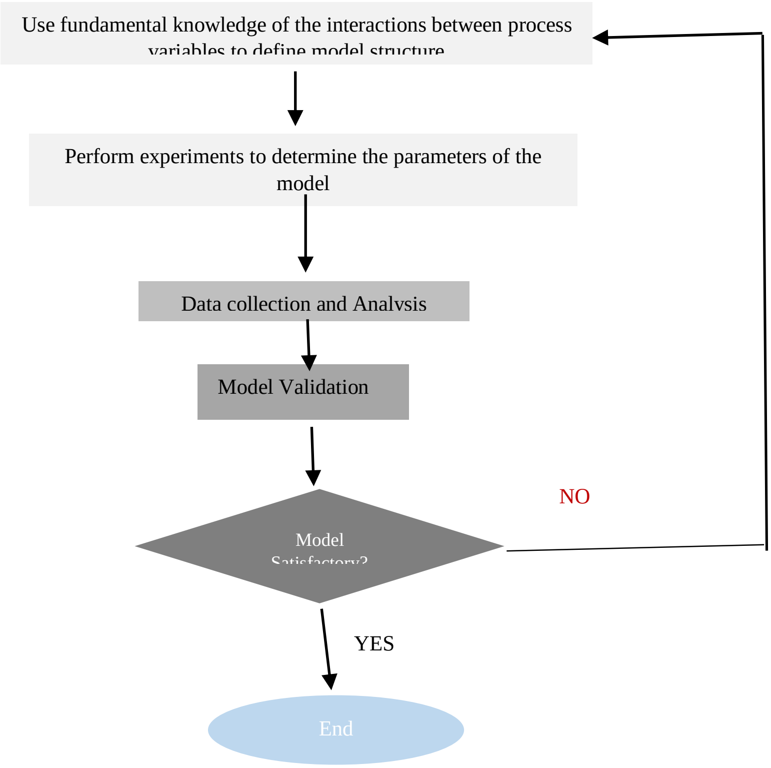

**Figure 2: Mechanistic Modeling Flowchart**

The total length of the seat and support of the legs needed for support of upper and lower legs of the $P_{(M)}95$ patient:

Dimension seat and support of the leg

$$L_{S-S} = L_S + L_{ls} \quad (4)$$

Dimension Total length (Dental chair)

$$L_{dent.chr} = H_{back\ rest} + H_{head-rest} + L_{seat} + L_{l-leg\ support} \quad (5)$$

The difference between maximal and minimal working field heights for $P_{(M)}95$ and $P_{(F)}5$ dentists respectively indicates *platform height* of the chair, which as well accommodates patients with motion impairment, wheel chair bound patients [14].

The platform height

$$H_p = H_{max} - H_{\min} \quad (6)$$

The length parameter of ‘elevat-able’ chair (headrest, backrest, seat, foot support) is determinable from Eqn. (1)-(5) for $P_M(95)$ patient of other races . The width and thickness parameters were adopted from ISO 6285.

The load of the chair becomes

$$W_{Chair} = \sum_j^i \{(V \times \rho) + m_c\} g \quad (7)$$

According to[14], at cylinder angle ($\beta$) , Weight at FOS

$$W_{FOS} = W_T\ x\ FOS \quad (8)$$

$$R = \frac{W_{FOS}}{Sin\beta} \quad (9)$$

With internal area of the hydraulic cylinder

$$A = \frac{R_{/cyl}}{p_{max}} \quad (10)$$

The ram load

$$W_{ram} = H_p \times A \times \rho g \quad (11)$$

The dead load of the eleveta-ble pantograph consisted of the chair and hydraulic ram

$$W_{dead} = W_{chair} + W_{ram} \quad (12)$$

Total load on the system is determined with

$$W_T = W_{dead} + W_{(Patient)} \quad (13)$$

Pascal’s Principle in Equa.(14) relates to ratio of force to area in any hydraulic system , provided that the piston are at the same vertical height and that friction in the system is negligible.

$$F_1 = \frac{A_1}{A_2} F_2 \quad (14)$$

Equa.(12) is substituted as $F_2$ in Equa.(14) to produce Equa.(15)

$$F_1 = \frac{A_1}{A_2}(W_T) \quad (15)$$

From Equa. (15), mechanical advantage and velocity ratio become

$$M.A = \mathrm{V.R} = \frac{R^2}{r^2} \quad (16)$$

The Pascal’s law represents governing operating principle of all kinds of hydraulic pump [15], and modern mechanical technology for determining platform displacement, displacement volume, hydraulic pedal travel, and likes.

## 3. RESULTS AND DISCUSSION

Equation 21 was demonstrated on the basis of 18 and 19, and the results of experimental runs were indicated on Table 1. Data visualization of dead load vs pedal force, total load vs pedal force and Pedal stroke vs platform displacement were displayed on Figure 3, Figure 4 and Figure 5 in that order.

**Table 1: Experimental Results**

| **Dead Load Experimentation** | | | | **Total Weight Experimentation** | | | |
|---|---|---|---|---|---|---|---|
| **Experi. Runs** | Desc. | Dead load (KN) | Pedal Force (KN) | **Experi. Runs** | Desc. Body mass(kg) | Total Load(KN) | Pedal Force(KN) |
| **1** | Hydrau. Piston | 0.04 | 0.01 | **1** | 60 | 1.15 | 0.211 |
| **2** | Seat Bracket | 0.1 | 0.025 | **2** | 65 | 1.2 | 0.221 |
| **3** | Chair system | 0.35 | 0.0875 | **3** | 75 | 1.3 | 0.241 |
| **4** | Chair system + Back Upholstery | 0.43 | 0.1075 | **4** | 78 | 1.33 | 0.247 |
| **5** | Trimmed Chair | 0.55 | 0.1375 | **5** | 80 | 1.35 | 0.251 |
| | | | | **6** | 84 | 1.39 | 0.259 |
| | | | | **7** | 93 | 1.48 | 0.277 |

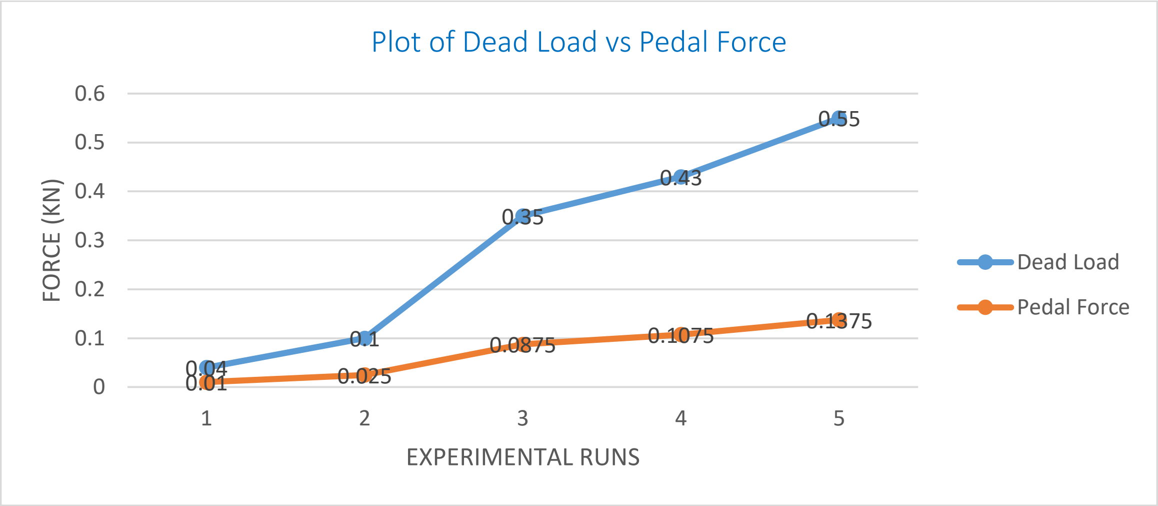

**Figure 3: Plot of Dead Load vs Pedal Force**

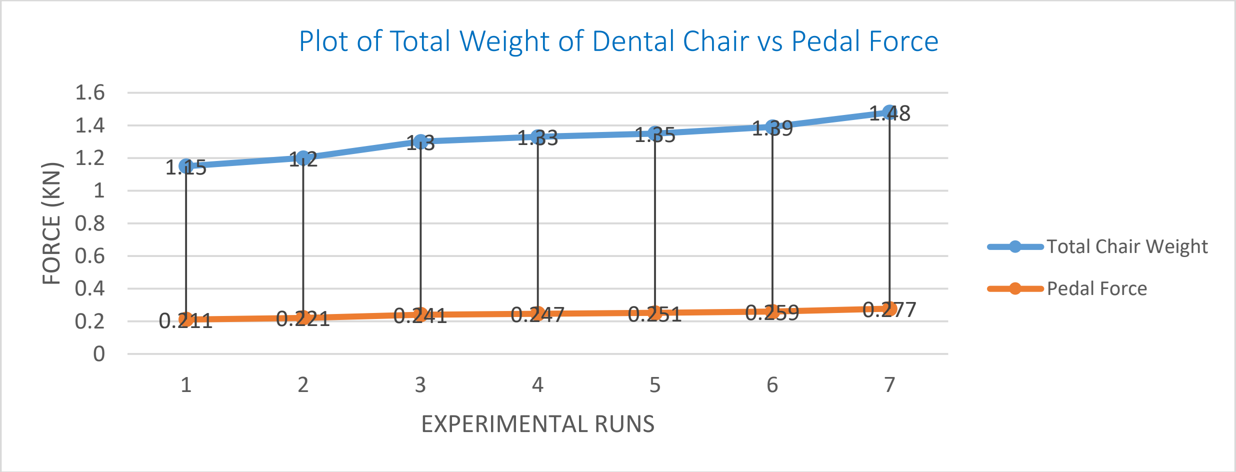

**Figure 4: Plot of Total Load vs Pedal Force**

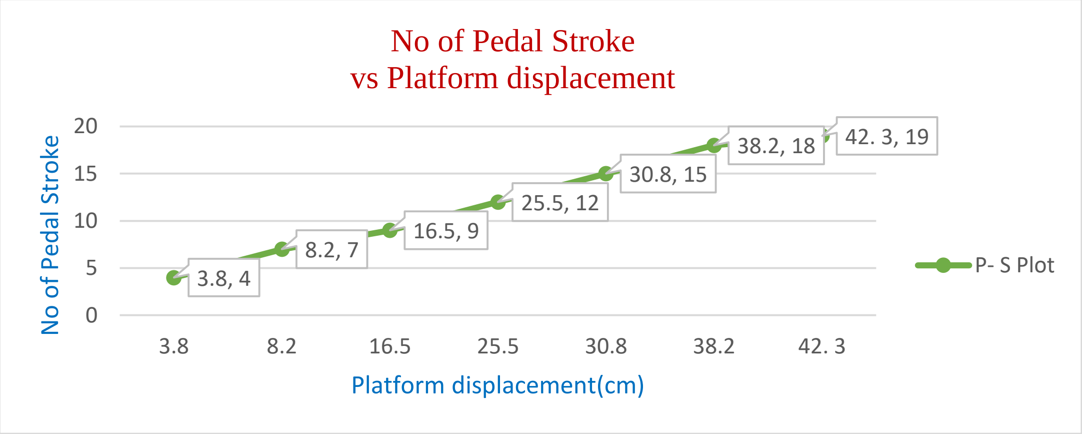

**Figure 5: Plot of No of Pedal Stroke vs Platform displacement**

Figure 3 shows that increase in material assembly of the chair from rudimentary hydraulic piston to trimmed chair increased the pedal force. Figure 4 indicated that increase of live load (patient) on the dead load increased pedal force more significantly. It makes a deductive sense that increase in load results to increase in pedal force, which corroborates Pascal’s law. Figure 5 shows that number of pedal strokes increases with platform displacement. According to [16], hydrostatic pumps are positive-displacement. It infers that the displacement volume of the pump, at each stroke increased platform displacement linearly. As could be observed, 19 pedal strokes were sufficient to raise 1.48-KN force through a designed platform height of 41cm. Mechanistic modeling are based on the fundamental laws of natural science and is a part of smart process development. The Pascal’s law becomes relevant in design of hydraulic parameters, including platform displacement. Noteworthy was a range of pedal force between 211N to 277N elevated 60kg -93kg fathom masses on improved dental chair design that corroborated input-output relationship [13]. This muscular load is tolerable for lower limb, in view of kinesiology table of percentage of total body weight of dentists. But, considering extreme case, where 277N is exerted for each of 19 pedal stroke in lifting 93kg patient through 41cm could be a lower limb ergonomic stressor, classified as forceful exertion [17]. The load in reclining dental chair is significant to ergonomics of the dentist and life-time dental practice. Through this simulation, technological improvement of the pump via enhanced velocity ratio, would significantly reduce pedal force and number of pedal strokes, and consequently, associated biomechanical effect on the dentists.

## 4. CONCLUSION

Pascal’s law provides simulation technique for design of hydraulic systems in modern mechanical technology. A 19 stroke of 15cm pedal travel were sufficient to raise maximum load of 1.48-KN force through a designed platform height of 41cm. Pedal force between 211N to 277N elevated 60kg -93kg fathom masses on improved dental chair design. It infers that improving the design of pump *viz-a-viz* cylinder velocity ratio impacts on ergonomics dentist and life-time dental practice.

### Compliance with Ethical Standards

Ethical clearance was not required at the analysis and optimization phase of engineering design model of improved dental chair design, hence, was unnecessary.

### Author contribution

All authors contributed equally to this work.

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### Data availability statement

The data that supports the findings of this study are available on request from corresponding author

### Disclosure of conflict of interest

The authors declare that there is no conflicts of interest

### List of Nomenclature

| | |
|---|---|
| $L_{back}$ | Length of backrest |
| $L_s$ | Length of seat |
| $L_{u.leg}$ | Length of upper leg |
| $L_{part_{lying\_on\_seat}}$ | Length of part of $P_{(M)}95$ patient lying on the seat |
| $L_{Leg\ support}$ | Length of leg support |
| $L_{lower\_leg}$ | Length of lower leg of $P_{(M)}95$ patient lying on the seat |
| $L_{Dental\_chair}$ | Length of dental chair |
| $H_{backrest}$ | Length of backrest of dental chair |
| $L_{s-s}$ | Length of seat and support of the leg |
| $L_{ls}$ | Length of leg support |
| $H_{headrest}$ | Length of headrest |
| $L_{u.leg}$ | Length of upper leg |
| $L_{part_{lying\_on\_seat}}$ | Length of part of $P_{(M)}95$ patient lying on the seat |

| | |
|---|---|
| $L_{Leg\ support}$ | Length of leg support |
| $H_{lifting_{lowerarg}}{}^{@15}$ | Vertical height of lower arm of $P_{(M)}95$ dentist lifted 15deg |
| $H_{elbow}$ | Height of elbow |
| $H_{shoe}$ | Height between mouth of patient and seat |
| $L_s$ | Length of seat |
| $H_{Max}$ | Height of wheelchair chair for $P_{(M)}95$ dentist(86cm) |
| $H_{min}$ | Height of chair for $P_{(F)}5$ dentist (45cm) |
| $H_p$ | Height of platform (distance between minimum and maximum recline-able height of dental chair) |
| V | Volume of material |
| $\rho$ | Density of hydraulic fluid |
| $m_c$ | Masses of other fittings |
| .g | Acceleration due to gravity |
| FOS | Factor of safety |
| $W_x$ | Weight of specified object |
| $A_1$ | Area of cylinder |
| $A_2$ | Area of ram |
| $F_1$ | Pedal force |
| $F_2$ | Total Weight($W_T$) |
| M.A | Mechanical Advantage |
| V.R | Velocity Ratio |
| $R$ | Radius of Ram |
| .r | Radius of cylinder |
| $P_{(x)}y$ | Anthropometric measurement of persons |
| $P_{max}$ | Maximum Pressure |

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