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Design, Modelling, Simulation, Fabrication and Performance Evaluation of a Portable Foot Operated Dispenser

[1]Onochie U.P., [2]Obilikpa S.C.,[3]Onwurah C., [4]Kwasi-Effah C.C., [5]Itabor N.A., [6]Damisah L. E, [7]Akingba O. O.

[1,3]Department of Mechanical Engineering, Faculty of Engineering, Alex Ekwueme Federal University, Ndufu Alike, Ebonyi State, Nigeria

[2]Department of Mechatronics Engineering, Faculty of Engineering, Alex Ekwueme Federal University, Ndufu Alike, Ebonyi State, Nigeria

[4]Department of Mechanical Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria

[5,6,7]National Centre for Energy and Environment, University of Benin, Benin City, Edo State

Corresponding Author: onochieuche@yahoo.com, Phone No: 08023778718

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Abstract

Hand washing and sanitizing have become a very essential part of our daily life especially in the era of COVID-19 pandemic. Most of the existing hand washing facilities on campuses is such that, the hands of the user is recontaminated after using the dispenser due to hand control of the system. This article reports a portable pedal driven soap and water dispenser which is developed for hand washing and sanitizing. The focus and objective of this study is to mitigate the risk of contracting or transmitting bacteria and virus during hand washing and to promote effective and efficient hand washing and sanitization practices across university campuses in line with COVID-19 protocols. The machine was designed based on a simple working principle to accommodate a person at a time. Modelling, simulation, fabrication and performance evaluation were considered in this study. All necessary engineering design specifications were also considered. An average standard height was used to position the tap at a height of 1.25m. The mechanism is very easy to operate due to the simplicity of the foot pedal press. Hence, it can be conveniently used by almost everyone regardless of their height. The performance evaluation of the machine was analysed using computer aided design software called Autodesk Inventor software for simulation to outline the places that stress and strain would occur as regards to force application. The efficiency of the machine is 90% and will replace the conventional veronica bucket (hand-operating tap) popularly used in most campuses in Nigeria. It is also very effective and will help to stop the spread of the COVID-19 infections and promote good personal hygiene.

1. Introduction

As the corona virus (COVID-19) pandemic continues to cause havoc all over the country and the world at large, engineers across the globe are currently involved in different research to complement the efforts of medical and health workers in combating the spread of the virus. Hand washing is the single most important piece of advice health experts can give to help individuals stay safe from COVID-19 [1]. COVID-19 appears to be transmitted person-to-person through respiratory droplets and close contact, as previously seen in SARS-CoV and

MERS-CoV, the two other zoonotic corona viruses. The necessity of practicing respiratory hygiene and hand hygiene, and using appropriate personal protective equipment have been highlighted. On 29 December 2019, the first four cases of an acute respiratory syndrome of unknown etiology among people linked to a seafood market ("wet market") were reported in Wuhan city, Hubei province, China [2]. This has brought about emergency lockdowns globally and its effects on health, wellbeing, business, and other aspects of daily life are felt throughout society.

There has been a direct detrimental impact on the global economy, raising concerns about the financial sustainability with effects predicted to continue as the virus fails to be contained. With the number of confirmed cases and its continuous spread, the priority is to reduce the rate of infection, and prevention of infection seems to be the best approach. To reduce the rate at which the coronavirus spreads, the world health organization (W.H.O) has given directives to improve our daily hygiene routines, such as frequent and correct washing of hands with soap under running water, use of hand sanitizers after every contact with people or surfaces, use of nose mask to prevent the virus infection through the mouth and nose and while carrying out these measures social distancing is a priority to stop the further spread from one person to another[3].

The whole world has been engulfed in a pandemic since the recent emergence of the Corona virus. The novel corona virus (SARS-CoV-2) is responsible for corona virus disease (COVID-19) pandemic which emerged in late December 2019 in Wuhan, in Hubei province of China, and within three months, had spread globally, prompting the World Health Organization (WHO) to declare it a threat to world health. SARS-CoV-2 belongs to the family coronaviridae (of the order Nidovirales, large, positive single-stranded RNA viruses), which are important human and animal viruses, in permanent circulation with four members of this family causing respiratory infections (common cold) worldwide. It is a beta corona virus that causes fever, headache, and respiratory problems such as cough and shortness of breath. Globally, there have been 116,135,492 confirmed cases of COVID-19, including 2,581,976 deaths, reported to WHO [4]. Nigeria has had 158,000, confirmed cases of COVID-19 with 1,964 deaths. 138,000 patients have so far recovered from the virus. As of 7 March 2021, a total of 249,160,837 vaccine doses have been administered [5].

According to the US Centre for Disease Control and Prevention, to prevent the spread of germs during the COVID-19 pandemic, you should also wash your hands with soap and water for at least 20 seconds or use a hand sanitizer with at least 60% alcohol to clean hands before and after touching your eyes, nose, or mouth, touching your mask, entering and leaving a public place [6]. Touching an item or surface that may be frequently touched by other people, such as door handles, tables [7], gas pumps, shopping carts, or electronic cashier register screens the single most important way of preventing the spread of infections is through Hand washing [1]; hands unwashed or poorly washed are a very common way of spreading many diseases such as cold, flu, ear infections, strep throat, diarrhea, and other intestinal problems. By handling food, touching doorknobs, shaking hands, and putting mouths on a telephone receiver, germs and viruses causing these diseases are passed on by such routine. Either in the offices, at home, in the market places, in the classroom, and so on in our daily activities, we practice one of these. Good hand washing practices have also been known to reduce the incidence of other diseases, notably pneumonia, trachoma, scabies, skin and eye infections, and diarrhea-related diseases like cholera and dysentery, according to World Health Organization (WHO) [8].

Foreign developed countries have produced advanced hand washing machines which are expensive for developing countries, there is a need to design low-cost and efficient machines to fight and contain the spread of COVID-19[9]. A water and soap dispenser machine with a contactless mechanism is ideal in limiting the transfer of the virus from one person to another [10]. The foot-operated soap and water dispenser machine is designed and fabricated to eliminate the risk of spreading COVID-19 when an infected person is about to wash off their hands from a tap[11]. This dispenser machine is designed to be used in any place a thorough hygiene routine and COVID19 protocol is observed such as in offices, classrooms, hostels, churches, public restrooms as well as domestic places. Ideally, the cap of the soap container and the water tap head needs to be opened before one can be able to wash off their hands. The design is made in such a way that a contactless mechanism is possible using pedals and tension springs to link the components of the mechanism [12].

In most public institutions, hands are used to control manually operated taps, which has the risk of re-contaminating the clean hands when used to close the tap after hand washing. To eliminate this action, two recommendations were highlighted in [13]; the use of the elbow and tissue paper to open and close the tap, but such recommendations are usually ignored. An effective solution that leads to a better hand washing is the foot-operated dispenser. There are several designs available in the literature.

A dispenser known as 'Pedal Tap' that reduces the growth and frequency of potent and infectious diseases spread like Ebola, Cholera, Flu on existing (manual) tap was presented in [14]. A pedal-operated sanitizer dispenser is a similar technology that has been developed in [9] to protect the hands against COVID-19. These dispensers and other available dispensing machines are single-purpose dispensers. That is, they can either dispense water or sanitizers. The gap in literature informed the nature of the design adopted in this study. In other words, a dual-purpose design that can dispense water and soap independently in the same machine is the novelty in this work.

Essentially, in our novel design, the materials for fabrication of the dispenser are locally available. Again, the advantages of this technology include but not limited to; ease of operation, no automation cost by electricity or batteries, and wastages would be reduced since the flow of water and liquid-soap is directly linked to the applied force on the pedals. This machine would complement the UNICEF WASH (water, sanitation, and hygiene) guidance note on COVID-19 prevention and control measures in schools as discussed in [1].

2.0 Materials and Method

The selection of material for any application is often based on the material's properties, suitability of use in the environment of operation, performance, design consideration, cost, and usability owing to their strength, durability, weight, and other mechanical properties. All the materials used were sourced locally such as the mild steel square pipe, angle iron, spring, sink, water container, water hose, push valve and tap, etc. The machine was designed based on a simple working principle to accommodate a person at a time. An average standard height was designed to position the tap at a height of 1.25m. Hence it can be conveniently used by almost everyone regardless of their height. The working diagram for fabricating the machine frame and other components is shown below. The various components welded and coupled together to make the machine are listed and explained in the section below. The design process of the hand washing machine was based on the functionality of individual parts.

2.1 Mechanical Design of the Dispenser

The components that make up the machine are mainframe, angle iron, 2-inch square pipes, 1-inch square pipes, water container, push valve, tap, sink, water hose, push angle valves, spring and pedals. The mainframe was first designed using CAD software (Autodesk Inventor). It has a dimension of 0.61mx0.64mx1.01m as depicted in the top and side views presented in Fig. 1.

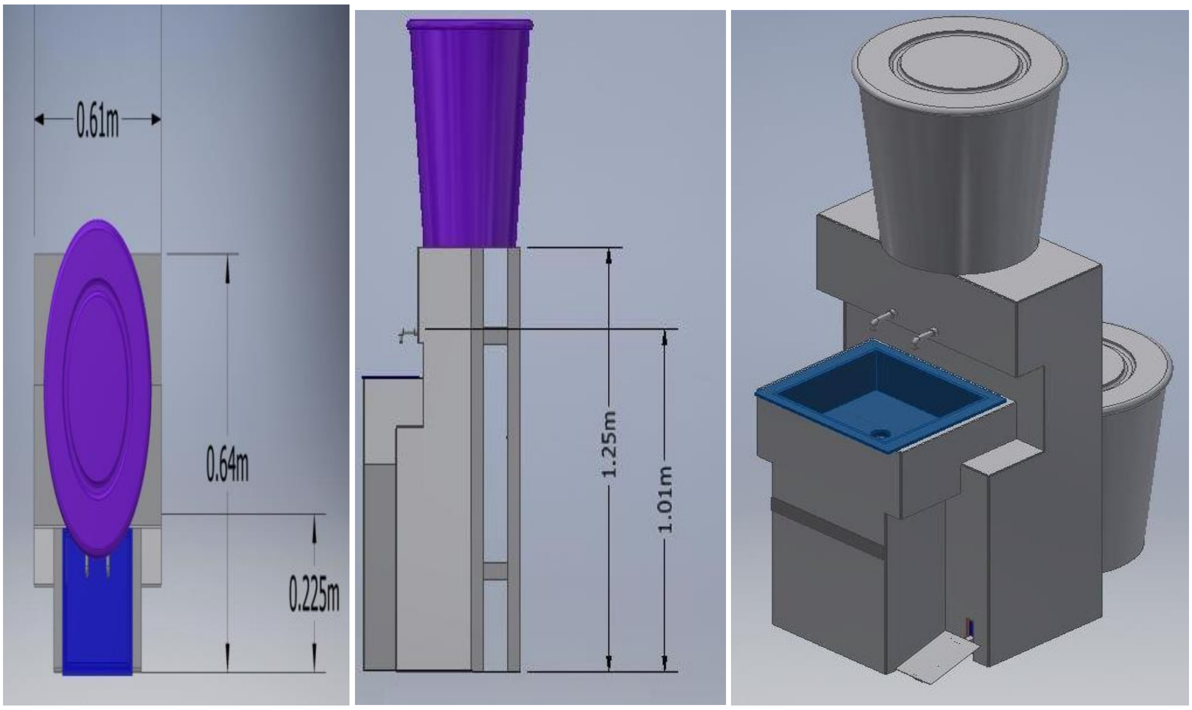


Fig. 1: Top, Side, and Isometric Views of the Dispenser

Soap and water translating pipes illustrated in Fig.2 are stationed near the frame having a translational movement inside a 2-inch square pipe fixed to the frame. As the inner pipe moves in a vertical linear motion, there is frictionless constraint applied to make sure the mechanism works as designed. These pipes are coated with water-resistant paints that increase their durability.

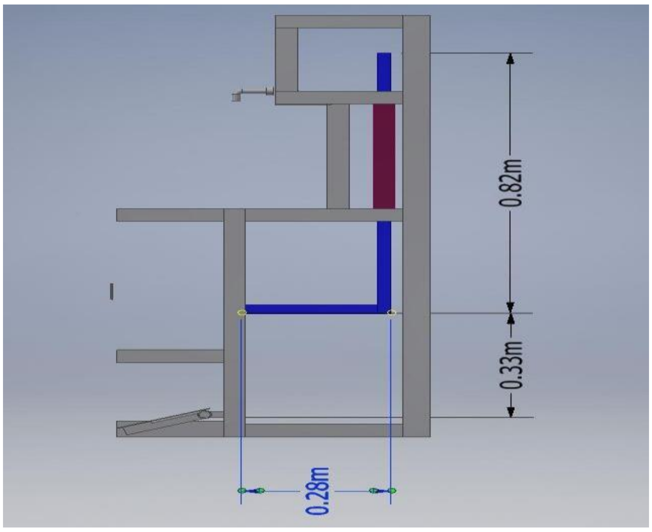


Fig. 2: Soap and Water Translating Pipes

2.1.1 Forces acting on the Machine

a. Load on machine

Force acting on the machine as load from the volume of water container placed on top of the machine is given by 30 litres.

If 1litre = 1kg, therefore, 30 litres = 30kg

Also 1kg = 10N, 30kg = 300N

But 1N = 0.225 lbf, 300N = 67.4427 lbf

b. Forces on pedal

Assuming that the pedal is acted upon by five different forces,

Forces applied on the pedal (F_p) = Mass x Acceleration due to gravity (1)

Force 1:

Given that Mass = 1.6 kg and acceleration due to gravity = 9.81m/s^2, we have that

F_{p1} = 1.6 x 9.81 = 15.696 kgm/s^2 =15.696 N

Force 2:

Given that Mass = 1.8 kg and acceleration due to gravity = 9.81m/s^2, we have that

F_{p2} = 1.8 x 9.81 = 17.658 kgm/s^2 =17.658 N

Force3:

Given that Mass = 2 kg and acceleration due to gravity = 9.81m/s^2, we have that

F_{p3} = 2 x 9.81 = 19.62 kgm/s^2 =19.620 N

Force4:

Given that Mass = 2.2 kg and acceleration due to gravity = 9.81m/s^2, we have that

F_{p4} = 2.2 x 9.81 = 21.582 kgm/s^2 =21.582 N

Force5:

Given that Mass = 2.4 kg and acceleration due to gravity = 9.81m/s^2, we have that

F_{p5} = 2.4 x 9.81 = 23.544 kgm/s^2 =23.544 N

2.1.2 Calculation for Spring Stiffness

Since the applied force at the pedal is proportional to the force required to stretch the spring fixed at the top of the soap and water shaft linkages, we calculate the spring stiffness from Hook's law of elasticity given by:

$$F = F_S = -K.\Delta E \quad (2)$$

Where FS= Spring force, K = Spring Stiffness and ΔE = Displacement/ change in translational distance and the negative sign showing work is done against the restoring force. From evaluation, the tension spring suitable for the machine mechanism has a spring stiffness of 25N/M.

2.1.3 Displacement along the Translating Pipes

Considering that the spring used is made of high carbon steel with spring stiffness of 25N/M, hence, from Equation 2.

Displacement 1:

F_{S1} = 15.696 N, -K = 25N/M

From Equation 2; ΔE_1 = 0.62784 m

Displacement 2:

F_{S1} =17.658 N, -K = 25N/M

ΔE_2 = 0.70632 m

Displacement 3:

F_{S1} = 19.620 N, -K = 25 N/M

ΔE_3 = 0.7848 m

Displacement 4:

F_{S1} = 21.582 N, -K = 25N/M

ΔE_4 = 0.86328 m

Displacement 5:

F_{S1} =23.544 N, -K = 25N/M

ΔE_5 = 0.94176 m

Table 1 show the comparison between the different theoretical displacements gotten from the value of the different forces on the pedal.

Table 1: Applied force -Displacement

S/N	Applied force (N)	Theoretical Displacement (mm)
1	15.696	0.62784
2	17.658	0.70632
3	19.620	0.78480
4	21.582	0.86328
5	23.544	0.94176

2.2 Modelling of the Mass of the foot exerted on the pedals

The force exerted by the dispenser pedal is proportional to the force driving the transmission part of the dispenser, the elastic force due to the spring-rod mechanism, and the viscous force.

Let,

$F = External force applied to the dispenser$

$m_1 = mass of discharge pipe$

$m_2 = mass\ of\ soap\ discharge\ pipe$

$a_1 = acceleration\ due\ to\ mass\ m_1$

$a_2 = acceleration\ due\ to\ mass\ m_2$

$b = Coefficient\ of\ Viscous\ force$

$v = Velocity\ of\ viscous\ force$

$k = Spring\ constant\ of\ the\ material\ (Mild\ steel)$

$x = Displacement\ of\ the\ elastic\ material$

The equilibrium equation of the force f is given as:

$$f = ma + bv + kx = m\frac{dx^2}{dt} + b\frac{dx}{dt} + kx \qquad (3)$$

For water dispensing, the force exerted f_1 can be expressed as follows

$$f_1 = m_1 a + bv + kx_1 = m_1\frac{dx_1^2}{dt} + b\frac{dx_1}{dt} + kx_1 \qquad (4)$$

Similarly, the applied force f_2, for soap discharging can be represented as equation (5)

$$f_2 = m_2 a + bv + kx = m_2\frac{dx_2^2}{dt} + b\frac{dx_2}{dt} + kx_2 \qquad (5)$$

The total force exerted for a complete handwashing operation can be deduced as;

$$F = f_1 + f_2 = m_1\frac{dx_1^2}{dt} + b\frac{dx_1}{dt} + kx_1 + m_2\frac{dx_2^2}{dt} + b\frac{dx_2}{dt} + kx_2$$

Hence,

$$F = m_1 \frac{dx_1^2}{dt} + b\frac{dx_1}{dt} + kx_1 + m_2 \frac{dx_2^2}{dt} + b\frac{dx_2}{dt} + kx_2 \quad (6)$$

But the weight of object W due to gravity is equivalent to its force,

That is,

$$W = F = mg$$

Thus,

$$W = m_1 \frac{dx_1^2}{dt} + b\frac{dx_1}{dt} + kx_1 + m_2 \frac{dx_2^2}{dt} + b\frac{dx_2}{dt} + kx_2 \quad (7)$$

Combining Equations 6 and 7

The mass of the foot m exerted on the pedals a complete hand washing operation can be evaluated using Equation (8);

$$m = \frac{m_1\frac{dx_1^2}{dt} + b\frac{dx_1}{dt} + kx_1 + m_2\frac{dx_2^2}{dt} + b\frac{dx_2}{dt} + kx_2}{g} \quad (8)$$

Assuming that the coefficient of viscous friction $b = 0$ for the two operations, we have equation (9)

$$m = \frac{m_1\frac{dx_1^2}{dt} + kx_1 + m_2\frac{dx_2^2}{dt} + kx_2}{g} \quad (9)$$

The analytical model used for estimating displacement was derived from Equation 1 as;

$$x = \frac{f - ma - bv}{k} \quad (10)$$

2.3 Finite Element Analysis (FEA)

The CAD software (Autodesk Inventor) was also employed to simulate the relationship between the force, displacement, and maximum stress of the device. This is a numerical method used to ascertain information on how a part, component, or machine behaves under some given conditions. During the simulation, the direction of the force and boundary conditions are defined as highlighted in Fig.3. The results of this analysis are presented in section 3.

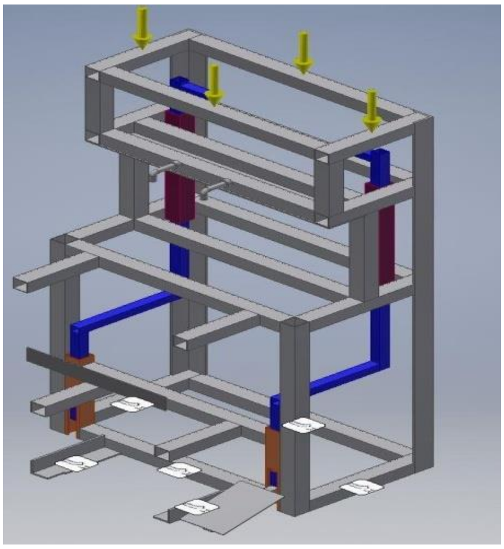


Fig.3: Direction of Applied Force (Load) on Machine

Table2: Mild steel Properties

Properties	Mild steel
Mass Density	0.283599 lbmass/in^3
Yield Strength	30022.8 psi
Ultimate Tensile Strength	50038 psi
Young's Modulus	31908.3 Psi
Poisson's Ratio	0.275
Shear Modulus	12513.1 ksi

2.4 Dispenser Fabrication

The dispenser was fabricated to operate based on a simple force-displacement mechanism. The foot-operated dispenser is made of metal and other non-metal materials. For the soap dispenser, the cap is operated by pressing the pedal with the foot. When the pedal is pressed, the spring attached to the inner movable pipe and outer fixed pipe extends and pushes the inner movable pipe downwards.

2.4.1 Working Principle of the Dispenser

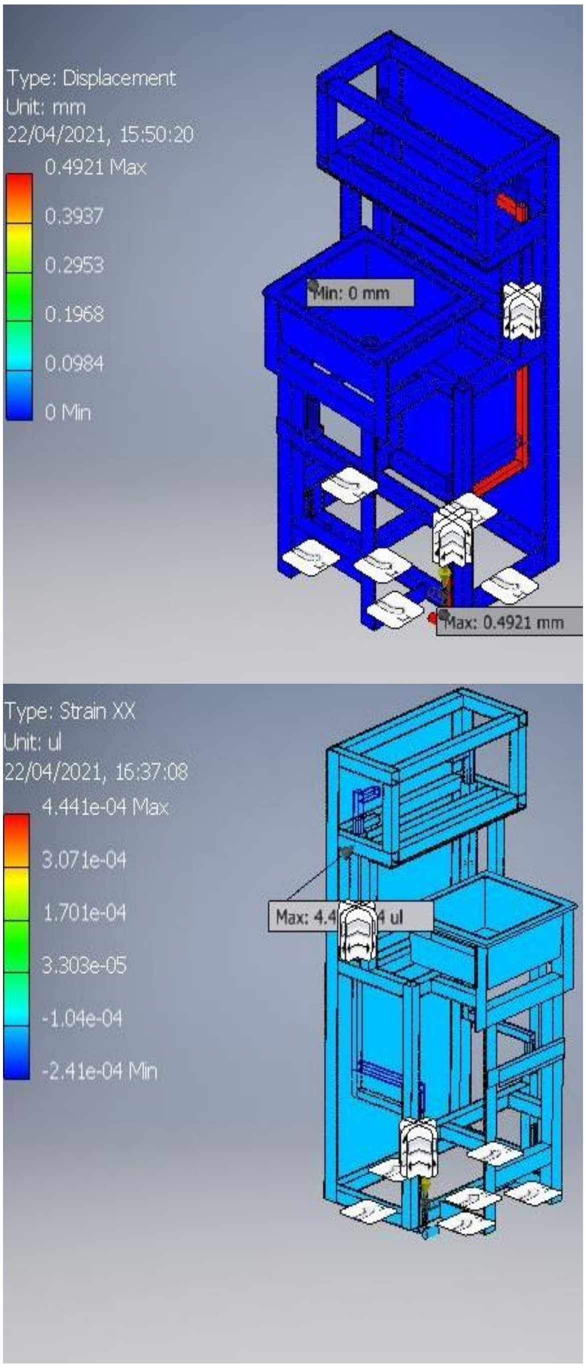
For this action to take place, the inner movable pipe should move downwards, causing contact between the bottle and the extended part which presses the cap. As the inner movable pipe moves downwards, the pressure is applied on the cap and the bottle starts dispensing soap through the tap head on the sink. The soap can come out of the nozzle because its viscosity is reduced making it easy to flow. The dispensing action of the soap bottle comes to an end when the pump is brought back to its original position by removing the force applied. When the force from the pedal is lifted, the pedal returns to its original position, so does the spring and the translating pipe. Thus, it returns to its initial position and stops dispensing soap. When soap is received from one tap head at the sink, the operator/user moves across and makes a press with his/her foot on the second pedal which controls the flow of clean water for washing the hands. Once the foot is pressed on the pedal, the translating pipe which seats on the push angle valve presses the valve head downwards to allow the flow of water through the valves to the basin where the contaminated hands are washed. After washing the hands, the tap is closed by the same spring action when the foot is released. The skeletal frame during fabrication and the fully installed dispenser are depicted in Fig. 4.

Fig 4: The skeletal frame and fully installed views of the Dispenser during Fabrication

3.0 Results and Discussion

3.1Simulation Analysis

The performance evaluation of the machine was analyzed using computer-aided design software called Autodesk Inventor software for simulation to outline the variation of stress magnitude within the system as regards force application. A typical FEA result is shown in Fig 5. From this result, the maximum displacement obtained when a force of 15.969N was applied on the pedal is 0.4921mm. The different results of this simulation are recorded in Tables 2 and 3.



(a) Maximum displacement **(b)** Maximum strain

Fig. 5: Finite Element Simulation result of force-displacement: (a) and (b)

From the simulation analysis of the soap pedal translating pipe and the water pedal translating pipe, the following can be deduced; The increase in force leads to an increase in translational displacement as depicted in Fig.6 and Fig.7., and thus, the stresses on the soap and water pedal translating pipes. Also, the increase in force leads to an increase in the strain on the soap and water pedal translating pipes, and the Von Mises stress on the soap and water pedal translating pipes. Likewise, the principal stresses on the soap and water pedal translating pipes are increased. During the FEA, It was observed that the increase in force leads to a decrease in the safety factor of the translating pipes. The results presented in Table 2 and Table 3 show that the derived model and FEA simulation closely predicted the behaviour of the force-displacement relationship of this machine, as these results are approximately the same as those obtained experimentally. The deviations are negligible errors which could be due to approximation during the computation.

3.2 Experimental Verification Analysis

The results of this experimental verification are presented in Tables 2 and 3.

Table 2: The force-displacement results for Analytical model, FEA simulation, and Experimental Verification (water dispenser)

S/N	Applied force (N)	Displacement (mm)		
		Analytical Model	**FEA Simulation**	**Experimental**
1	15.696	0.49	0.48	0.50
2	17.658	0.61	0.65	0.62
3	19.620	0.68	0.70	0.77
4	21.582	0.84	0.85	0.85
5	23.544	0.93	0.95	0.92

Table 3: The force-displacement results for Analytical model, FEA simulation, and Experimental Verification (Soap dispenser)

S/N	Applied force (N)	Displacement (mm)		
		Analytical Model	**FEA Simulation**	**Experimental**
1	15.696	0.63	0.64	0.59
2	17.658	0.70	0.72	0.61
3	19.620	0.71	0.80	0.67
4	21.582	0.78	0.88	0.87
5	23.544	0.86	0.96	0.89

The fabricated machine was tested to force different applied weights on the pedal. Five different known objects of known mass were suspended on the pedals of the machine. Due to the difference in translating pipes' mass and geometrical properties, different displacement results were obtained for the water and soap dispensing systems.

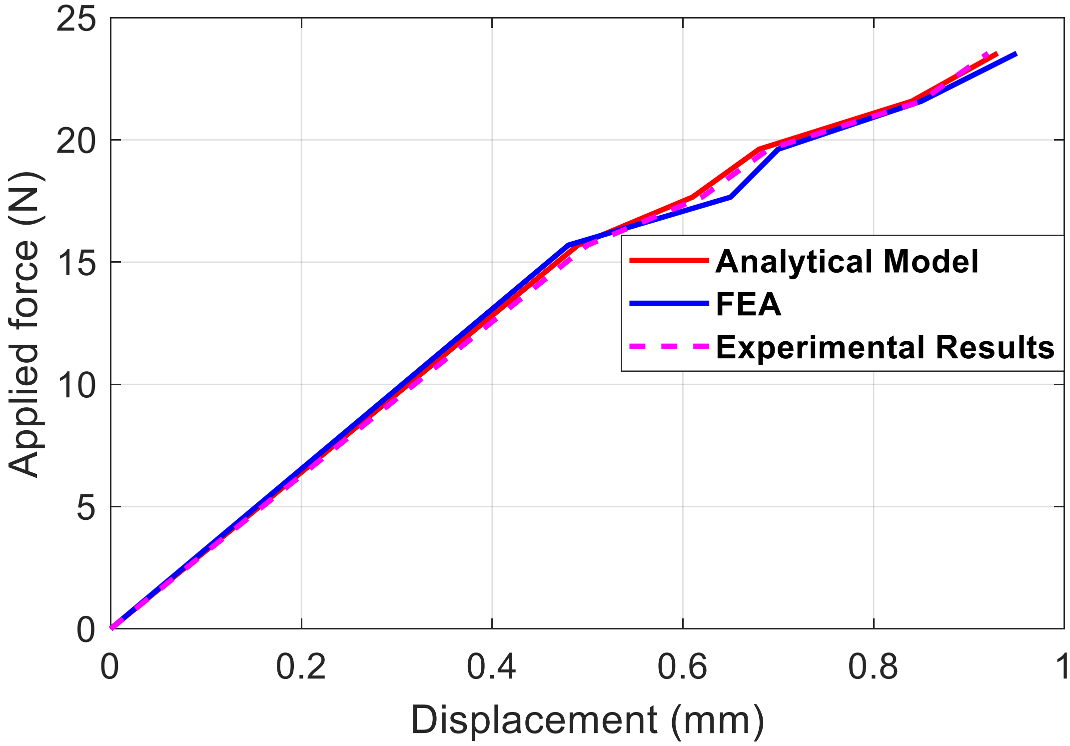


Fig. 6. Force-Displacement relationship for water dispenser

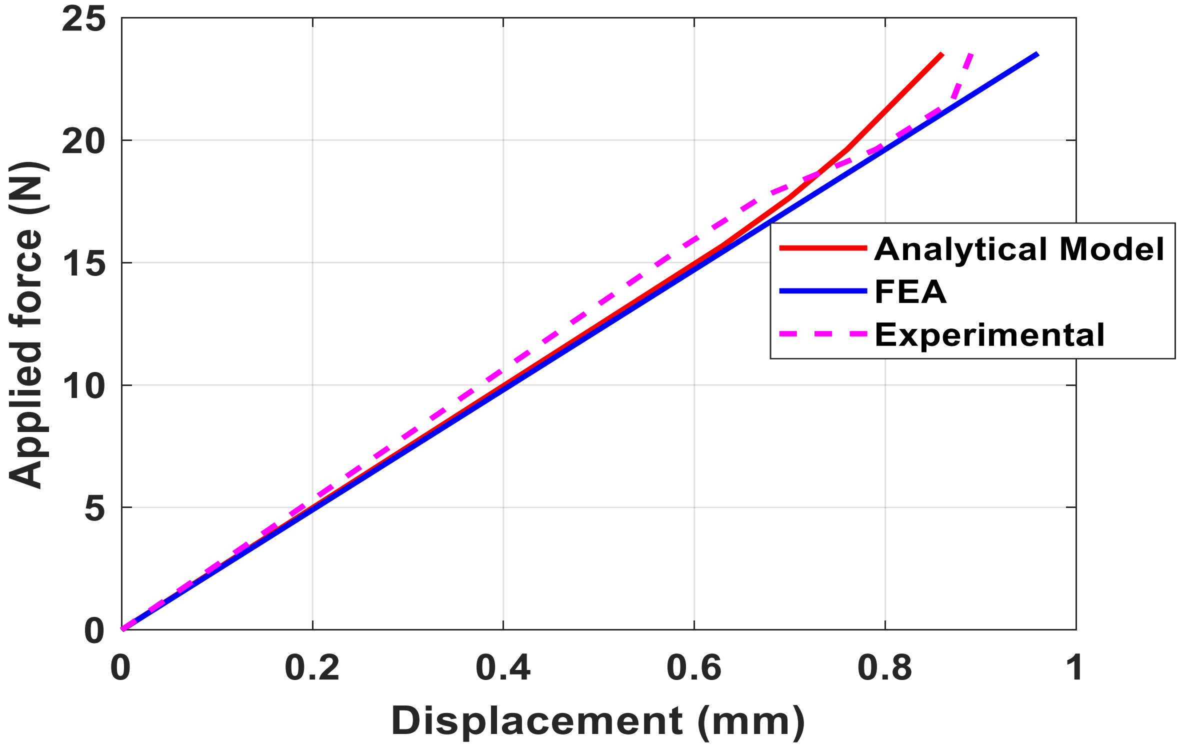


Fig. 7. Force-Displacement relationship for soap dispenser

4.0 Conclusion

The need for a contactless way of maintaining hygiene through hand washing cannot be overemphasized. A foot operated hand washing machine capable of dispensing liquid soap and water for hand washing was designed and fabricated. The operation efficiency relative to the foot-operated dispensers was estimated to be 90%. This device can be used in any firm or institution to reduce the spread of COVID-19 and maintain good hygiene.

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