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[1.]Idehai Olayemi OHIJEAGBON, [2.]Jayeola Femi OPADIJI,
[3.]Emmanuella Aghogho EMEFE, [4.]Olayinka Olajumoke AREMU

DEVELOPMENT OF A LUMBAR SPINE AND EXTENSOR ORTHOPAEDIC RECOVERY SYSTEM

[1,3,4.]Department of Mechanical Engineering, University of Ilorin, Ilorin, NIGERIA
[2.]Department of Electrical Engineering, University of Ilorin, Ilorin, NIGERIA

Abstract: A simple lumbar spine (low back) and extensor (muscle) orthopaedic recovery system have been developed in this study. The system is designed to assist in overcoming logistics constraints associated with treatment and recovery of musculoskeletal ailment and neurologic injuries by implementation of controlled therapeutic exercise without unwarranted complexities and obstructions especially for low income earners. The structural frame comprising of the head rest, back rest, bed rest, hand rest and the leg support was designed and fabricated. The system derives its reciprocating motion from the combination of an electric motor and a slider crank mechanism. The system was designed for a maximum body mass of 125.80 kg. The slider crank mechanism attains a maximum stroke of 175 mm. The orthopaedic recovery system would go a long way to effectively mitigate the socioeconomic burden and condition of individuals suffering from chronic musculoskeletal pain and impaired function at the lumbar area. Furthermore, the living condition, resourcefulness and productivity of victims of musculoskeletal impairment would be greatly improved; and sickness related expenses are also expected to reduce due to enhanced recovery rate of low back orthopaedic patients.

Keywords: Recovery system; orthopaedic patients; therapeutic exercise; productivity

1. INTRODUCTION

Orthopaedic related problems are health disorders usually associated with muscles, ligaments and joints. Some of these disorders are arthritis, elbow pain, neck pain, foot pain, knee pain and low back pain [1]. Low back pain must not be ignored as it is the second most common reason for people to consult a physician, affecting up to 70% of adults [2]. Musculoskeletal conditions have been identified worldwide as a major burden on individuals, health systems, and social care systems, with indirect costs being predominant. This burden was recognized by the United Nations and WHO, by endorsing the years 2000–2010 as the Bone and Joint Decade [3]. If such health issues are not adequately addressed, it may greatly hamper the productive workforce of any society or organization, and also impoverish many families. Low back pain may be caused by strenuous activities, exposure to continual vibrations, degeneration of the vertebrae, traumas or injuries. Low back pain is one of the most prevalent and costly orthopaedic problem in the society, and was predicted that 80% of adult will experience low back pain in their lifetime and 34% who experience low back pain will have recurring episodes [4]. Conventional treatments for low back pain include medication, use of hot or cold packs, stretching and strengthening exercises [5]. It has been established that post-treatment exercise programs can prevent recurrences of back pains [6]. Rehabilitation robotics and devices have been employed in recent times to assist therapeutic interventions associated with musculoskeletal conditions [7]. However, many individuals do not have access to hospitals with fully equipped comprehensive rehabilitation facilities because of limitations such as long distances and high cost [8]. Availability of simply operated recovery systems can greatly enhance physiotherapy health care workers especially in remote locations to assist patients and the populace in general with specific exercises, joint mobilizations and strength training needed to restore maximum movement and functional ability [9-13].

Furthermore, small healthcare service providers that cannot afford to procure the sophisticated rehabilitation robotics systems would have the opportunity to own the simpler and cheaper recovery systems developed in this study.

This study attempts to bridge the gap between patients with low back pains and required physiotherapeutic treatment. This is imperative in order to maintain a healthy and productive society. Hence, the need for the development of an appropriate technological system for physiotherapy and gradual recovery of orthopaedic patients with low back disorders to gain relief and undergo therapy with little or no human intervention at affordable cost.

2. DESIGN ANALYSIS

— Description of the Low Back Orthopaedic Recovery System

For the lower back recovery system under consideration, it consists of four major segments, which are, the head rest, back rest, arm rest and lower body (bed) rest respectively. The system is designed to operate on the principles of electromechanical and slider crank mechanism system devices. An electrical motor was used to transmit its rotary motion to a reciprocating motion via connecting linkages to the back rest. This ensures a continuous exercise of the lower back or lumbar spine and extensor joint. The speed of the motor and consequently that of the back rest is regulated by an electric circuit which interfaces with the motor in order to control the operational speed of the system to suit the particular needs of recovery of exercised patients. The system is also provided with leather straps to fasten the body to the back and bed rest respectively during operation.

— Material Selection

The material selection and fabrication of various parts of the designed system was based on the following factors; availability of the material, suitability of the material for the working condition in service, cost of the material, strength of the material, and ease of fabrication. Hence, the material used for the construction of the low back orthopaedic recovery system was mild steel.

— Design Calculations

» Design dimensions of the recovery system

Common anthropometric measurements data for the seated position which may be used in designing seating for both male and female are presented in Table 1 [14]. Available anthropometric data given in Table 1 were used as guide to estimate the body dimensions used for the design of the framework of the recovery system. The estimated dimensions of the major parts of the system are stated as follows:

1. Head rest: design length = 0.329 m
2. Back rest: design length = 0.587 m
3. Lower body (bed) rest: design length = 1.034 m
4. Arm rest: design length = 0.400 m

Table 1. Common anthropometric measurements for seated position

Measurement	Female 5th – 95th% (mm)	Male 5th – 95th% (mm)	Overall Range 5th – 95th% (mm)
Sitting Height	795.02 - 909.32	853.44 - 972.82	795.02 - 972.82
Sitting Eye Height	1082.04 - 1239.52	1176.02 - 1336.04	1082.04 - 1336.04
Waist Depth	185.42 - 271.78	198.12 - 289.56	185.42 - 289.56
Thigh Clearance	533.40 - 622.30	584.20 - 680.72	533.40 - 680.72
Buttock-to-Knee	541.02 - 640.08	568.96 - 668.02	541.02 - 668.02
Knee Height	502.92 - 589.28	543.56 - 635.00	502.92 - 711.20
Seat Length/Depth	429.26 - 518.16	449.58 - 535.94	429.26 - 535.94
Popliteal Height	381.00 - 459.74	424.18 - 505.46	381.00 - 505.46
Seat Width	368.30 - 457.20	353.06 - 436.88	353.06 - 457.20

Source: Openshaw and Taylor [14]

» Design loads on the recovery system

The approach used by Ohijeagbon *et al.* [15] in the study: developmental design of an orthopaedic recovery system which was adopted from Haley [16] to determine the segmental masses from the relative proportions of segmental volumes, for total body masses was used to estimate the mass distribution of the body mass segments employed as the design loads for the present design analysis as presented in Table 2. Consequently, the maximum design load of the system is 1,234.10 N.

Table 2. Mass distribution of the body segments

Body segment	Mass (125.80 kg)	Weight (1,234.10 N)
Head	8.40	82.40
Neck	2.20	21.58
Thorax	49.80	488.54
Abdomen	4.80	47.09
Pelvis	23.60	231.52
Thigh	19.60	192.28
Calf	7.60	74.56
Foot	2.00	19.62
Upper arm	4.00	39.24
Fore arm	2.80	27.47
Hand palm	1.00	9.81

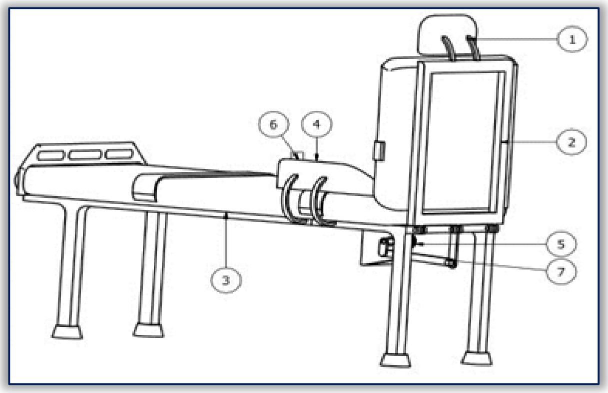

Figure 1. Isometric view of the lumbar spine (lower back) orthopaedic recovery system
1-Head support 2-Back support 3-Lower body support (bed) 4-Fore arm support 5-Transmission link connection to electric motor 6-Electric motor controller 7-Connecting rod

Therefore, the mass distribution of the body segments for a body weight of 1,234.10 N (125.80 kg) were used in conjunction with the estimated dimensional lengths to design the recovery system. Furthermore, the design load and dimensions were used to determine the maximum bending moments and shear forces in the system. Hence, the factor of safety was computed to determine the viability of the designed system. The isometric view of the lumbar spine (lower back) orthopaedic recovery system is shown in Figure 1. The parts labelled 1, 2 and 3 in Figure 1, namely, the head support (AB), back support (BC) and lower body support (CD) are represented in the free body diagram as shown in Figure 2.

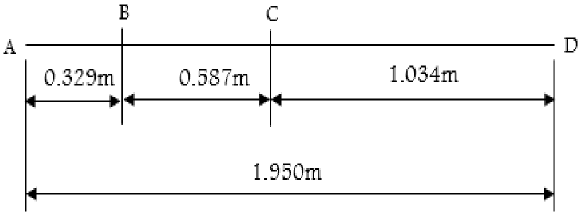

Figure 2. Free body diagram showing the total length of the segments 1, 2, 3 of Figure 1

— Analysis of the maximum bending moment of the system

The maximum bending moment of the system was determined by applying the equation of static equilibrium on the width of the bed with the critical load acting at the location C of Figure 2, which is the intersection between the back support and the lower body support. The free body diagram of the width at the location C is shown in Figure 3.

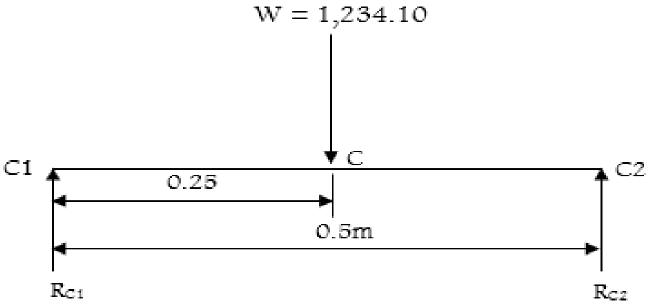

Figure 3. Free body diagram of the width of the bed at location C of Figure 2

Hence, from Figure 3, the reaction forces, R_{C1} and R_{C2} and the maximum bending moment are obtained as:

$$R_{C1} = R_{C2} = W/2 = 617.05\,\mathrm{N} \quad (1)$$

$$M_{max} = 0.25 \times R_{C1} = 0.25 \times 617.05 = 154.26\,\mathrm{Nm} \quad (2)$$

Analysis of factor of safety for the system

The maximum stress on the system was determined as:

$$\sigma_{max} = M_{max} \cdot y/I \quad (3)$$

where, σ_{max} is the maximum stress, M_{max} is the maximum bending moment, y is the distance from the neutral axis to the outer surface, and I is the second moment of area. The second moment of area of a solid cross-sectional surface and the centroid are expressed by:

$$I = wb^3/12 \quad (4)$$

$$y = b/2 \tag{5}$$

where, w is the width and b is the breadth respectively. A standard width and breadth of 50 mm and 20 mm were used for the design. By using the known cross-sectional dimensions of a standard pipe, the second moment of area and consequently the maximum stress can be evaluated. Hence, the factor of safety determined as:

$$n = \sigma_y / \sigma_{max} \tag{6}$$

where, n is the factor of safety and σ_y is the yield stress of the material. The yield stress of mild steel used in this study is 228 MPa [17].

— Design of the slider crank mechanism

Since the slider crank mechanism was operated on the back rest, therefore to obtain the maximum stroke, the position of the center of the crankshaft which lies under the bed rest, was estimated to be at a distance of $1/4$ of the bed rest from the edge between the back rest and the bed rest (Figure 1). Therefore, distance of the center, O of the crank shaft from the edge of the bed rest was determined as: $1/4 \times 1034 = 259mm$.

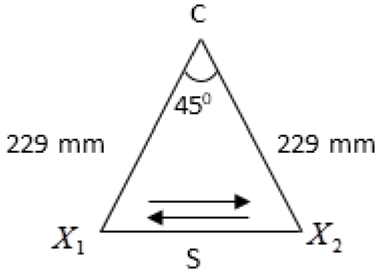

Figure 4. Angle of oscillation of the back rest and connecting link

The combined length of the back and head rest was constrained to oscillate through an angle of 45°. The oscillating end of the connecting rod $X_1 - X_2$ as shown in Figure 4 possesses a maximum stroke of S, and connected to the intersection between the bed and back rest C as indicated in Figure 4. The length of the link connecting X to C was determined as one quarter of the combined length of the back and head rest: $L_3 = 1/4 \times 916 = 229\text{mm}$. The link XC is fixed to the frame of the back rest, such that they oscillate together during operation. Therefore the maximum stroke was determined as:

$$S^2 = X_1C^2 + X_2C^2 - 2\times X_1C\times X_2C\times \mathrm{Cos}\,45^0 \tag{7}$$

Figure 5 shows the slider crank mechanism. Where, X_1 represent the inner dead stroke, X_2 represent the outer dead stroke, L_1 represent the offset distance, L_2 represent the radius of the crank shaft, L_3 represent the length of the connecting rod, β represent the imbalance angle and S represent the maximum stroke respectively.

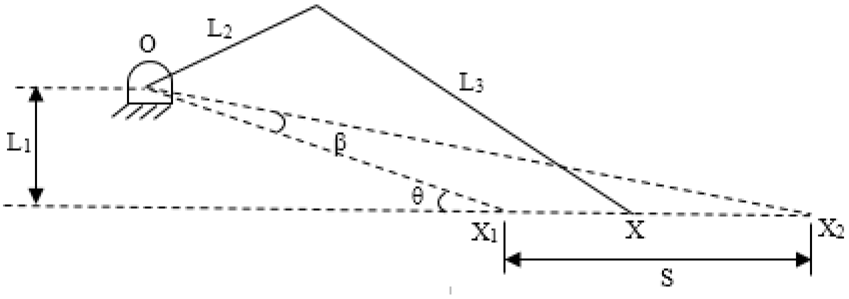

Figure 5. Free body diagram of the slider crank mechanism

The angles β = 12° and θ = 24°, while the lengths L_1, L_2 and L_3 where determined as follows [18]:

$$L_1 = \frac{S[\mathrm{Sin}\theta \times \mathrm{Sin}(\theta - \beta)]}{\mathrm{Sin}\beta} \tag{8}$$

$$L_2 = \frac{S[\mathrm{Sin}\theta - \mathrm{Sin}(\theta - \beta)]}{2\mathrm{Sin}\beta} \tag{9}$$

$$L_3 = \frac{S[\mathrm{Sin}\theta + \mathrm{Sin}(\theta - \beta)]}{2\mathrm{Sin}\beta} \tag{10}$$

— Power requirement of the electric (DC) motor

The power required by the electric motor was determined by:

$$P = T \cdot \omega = F \cdot L_2 \cdot \omega \tag{11}$$

Where, P is the rotational mechanical power of the motor, T is the Torque (Nm), ω is the angular velocity (rad/sec), F is the total load (N) on the crank. The total load was obtained as the product of the factor of safety and the sum of load of head, load of neck, load of trunk, load of upper arm, load of abdomen and load of pelvis:

$$F = n \times (\text{load of head} + \text{load of neck} + \text{load of trunk} + \text{load of upper arm} + \text{load of abdomen} + \text{load of pelvis}) \tag{12}$$

— **Supplementary accessories**

Resistive speed controller: A resistive speed controller device was used as a DC motor speed controller due to its simplicity in its design architecture and its availability compared to other types such as the pulse width modulator (PWM). The advantage of a pulse width modulator (PWM) over the resistive speed controller is that it supplies a full voltage to the motor thereby producing more torque in the motor during motor speed control in contrast to the resistive speed controller which presents a reduced voltage to the load, so that the torque in the motor reduces.

Shock absorber: A shock absorber was necessary in the design because it helps to absorb or damp the shock impulses developed in the systems. Any vibration or shock that was supposed to be transferred to the human body is damped out by the shock absorber.

3. RESULTS AND DISCUSSION

The orthographic view of the developed lower back orthopaedic recovery system is shown in Figure 6. The basic dimensions of the system are head rest, 0.329 m, back rest, 0.587 m, bed rest, 1.034 m, and arm rest, 0.400 m respectively. Other dimensions of the system are height and thickness of bed rest, 0.600 and 0.025 m, length and span of leg support, 0.570 and 0.500 m and width of bed, 0.550 m. The system was designed for a maximum load of 125.80 kg. With a standard width and breadth of 50 mm and 20 mm, the maximum bending moment, maximum stress and factor of safety of the system where obtained as 154.26 Nm, 46.28 MPa and 4.9 respectively.

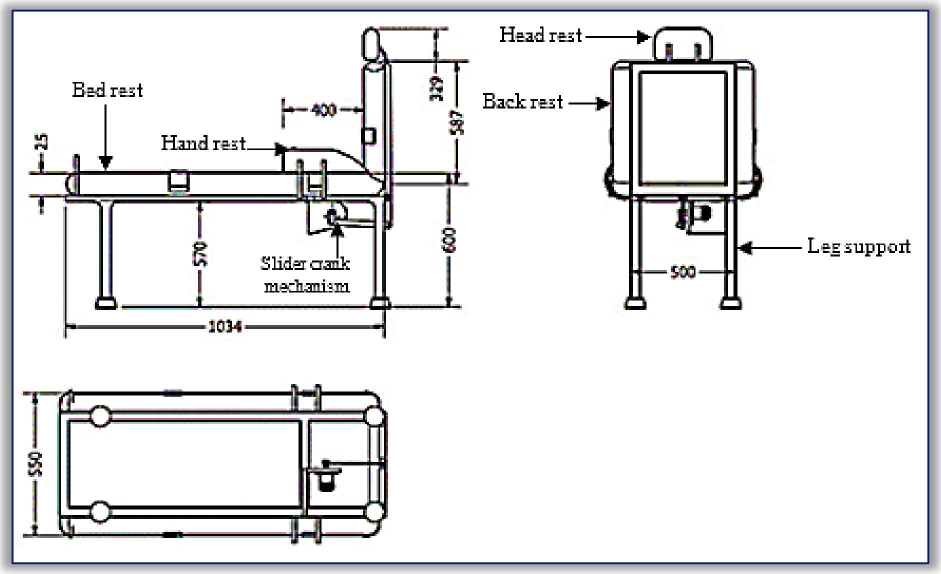

Figure 6. Orthographic view of the lower back orthopaedic recovery system

The maximum stroke of the slider crank mechanism was determined as 175 mm. The offset distance, radius of the crank shaft, and length of the connecting rod of the slider crank mechanism of the recovery system were respectively determined as 71, 84 and 259 mm accordingly. The total load exerted on the crank shaft was determined as 910.37 N, and was used to estimate the horsepower rating of 0.1 *hp* for the required electric motor.

The performance analysis of the system shows that the system can be operated on three levels of speed, low, 6 rev/min, medium, 12 rev/min and high, 18 rev/min speeds respectively. The time for the forward and retraction strokes of the system was obtained as 5 and 3 seconds at low speed, 3 and 2 seconds at medium speed, and 2 and 1 seconds at high speed respectively. The tests result shows that the load carrying capacity of the system was lower at a lower speed. The load carrying capacity of the system was found to be about 35 kg at low speed, while the system could carry a load of up to 125.80 kg at a higher speed. This indicates that the slider crank mechanism developed greater torque when operating at higher speeds.

The overall cost of developing the lower back recovery system was about one hundred thousand naira, that is, about two hundred and seventy-eight US dollars ($278). This is by far cheaper to modern sophisticated robotics rehabilitation recovery systems which could run into hundreds of thousands of dollars. Also, the developed recovery system does not necessarily require any special skillset to operate in contrast to that of robotics system whose required skillset may not be easily available in many remote locations or developing countries comprising medium and low-income earners.

4. CONCLUSION

An orthopaedic recovery system to facilitate treatment and recovery of patients in need of physiotherapy in the lower back musculoskeletal body function have be designed and fabricated in this study. The system has an overall dimension of length, 1.034, width, 0.550 m and height, 1.516 m respectively. The 125.80 kg capacity body mass system derives its reciprocating motion from the combination of a 0.1 hp electric motor and a slider crank mechanism; and the motion was regulated by a resistive speed DC motor speed controller. A maximum load of 910.37 N was exerted on the shaft of the slider crank mechanism which was capable of attaining a maximum stroke of 175 mm. The recovery system is simple in function and in handling, hence does not require any rigorous training or skillset to operate. Furthermore, it can easily be produced with simple available materials and devices at a relatively cheap cost of only $278. The system requires the inclusion of a spring system to assist in retarding the speed of the back rest during retraction, and consequently help to further dissipate the momentum of the back rest and resulting vibration. In addition, the offset slider crank could be redesign and replaced by an in-line slider crank which is expected to produce a lower retraction speed in comparison to that of the offset.

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