Design of a Robotic Wearable Shoes for Locomotion Assistance System

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Abstract. The inability of a patient to move freely or one part of the body paralysis is an indication of stroke disease or symptoms. This challenge resulted in locomotion of body impairment. In this research, a robotic wearable locomotion assistance system in a pair of shoes is developed using closed-control of mechatronic and embedded system approach. This is to render assistance for the patient impairment locomotion, to improve the passive control and design of orthoses for the structural support of the people with moderate lower-limb weaknesses. The adaptation of this system is varied in position during motion instantaneously and to manage the stiffness of the joint. This wearable robotic shoe helps the paralytic leg (prosthesis) to track the position of the non-paralytic leg using awareness of the sensor and transceivers to establish the communication between the foot posture and support. It also helps the stroke patient with orthoses or prostheses of (foot and leg) to walk linearly in an upright position (maintaining alignment of foot and leg), improving balance, and support the arch and heel of the patient. This system prototype was implemented and tested, and the results show high accuracy in linear tracking and alignment.

Keywords: Assistance system · Embedded system · Paralytic leg · Robotics · Wearable device

1 Introduction

The recent advancement in the robotic system and embedded wearable devices using wireless sensor networks (WSN) has been widely developed for the rehabilitation, human disability assistance, and monitoring health status in biomedical professionals [1, 2]. These systems are sophisticated mechatronic technology equipped with sensors and powerful processing units to exploit real-time information that facilitates independent training during the exercise or enable patient-tailored assistance for locomotion [3, 4]. A wearable robotic system is an innovative rehabilitation insight for individuals (patients) with disabilities [5]. This includes muscle weakness, neurological or muscular disorders [6, 7], stroke, and spinal cord injury which ends-up with loco-motion difficulty (walking or arm movements). Stroke is one of the major and com-mon disability diseases among people of this age that required serious attention to rehabilitation. This disease is seriously

S. Misra and B. Muhammad-Bello (Eds.): ICTA 2020, CCIS 1350, pp. 689–702, 2021.
https://doi.org/10.1007/978-3-030-69143-1_52

affecting humans as a result of poor flowrate in the blood to the brain. The stroke challenges can be Ischemic (inadequate or poor flow rate of the blood to the brain ensued from thrombosis and embolism). The second is hemorrhagic (bleeding) caused by intracerebral or subarachnoid hemorrhage. It is affirmed that stroke affects about 795,000 individuals every year in the USA and recorded as the third disease that leading to emergency death [8, 9].

The stroke disease consequences include body locomotion inability, part of the body paralyzes, speaking difficulty, dizziness, and loss of vision [10]. The National Health Interview Survey (NHIS) data reveal that people with ischemic stroke challenge increases among adolescents and young adults between 5–44 years [11]. It is discovered that about 10% of people between 18–50 years of age were affected with stroke, while the percentage of the people above 50 years are very high and rampant. This symptom can either be temporary or permanent in human if urgent medical attention is not taken. It can result in poor locomotion in humans, stammering, and many others [12]. Therefore, this condition can be improved or supported by taking advantage of the existence of the neuro-rehabilitation robotic system.

A mechatronics system is a typical robotic or an embedded system-on-chip (ESoC) that preferences change in signals from the environment using sensors, process it for the output response using controllers [13, 14], and transform such signal to the motion or actions (actuator). This digitally controlled system usually comprises mechanical systems, sensors, actuators, and microcontroller chips [15].

The design of a mechatronics system (robotics) for neuro-rehabilitation therapy de-pends on the embedded microchip technology [16]. It plays a fundamental role in neuroscience and promotes the recovery of the brain that is utilized for body control. This human mechanism assisting and guiding in the disability of humans to perform some tasks during sensory and coordination in the body system. The motivation of robotic-aided neuro-rehabilitation system design in this research was due to recent scientific evidence in neuroscience that described a physical exercise in the movement action [17]. It promotes a significant effect on the process of neurogenesis by speeding up basic mechanisms that are involved in neural plasticity [18, 19]. The rehabilitation robotic-aided design (RRAD) needs to meet users' requirements, adapt to human performance and guarantee safety, robustness, reliability, comfort, and freedom of movement while pursuing the effectiveness of the treatment. Numerous research efforts have been made towards neurorehabilitation assistance for stroke patients, tremor disorders in huntingtin disease and locomotion impairments development [20].

2 Related Work

A single-joint wearable robotic knee orthosis (RKO) for adult stroke survivals is developed for stroke patients' locomotion. A preliminary report on the efficacy of a hybrid assistive limb in post-stroke hemiplegic patients is proposed for post-stroke assistance [21]. This hybrid assistive limb and a knee-ankle foot orthosis system were tested with 16 stroke patients, which prove efficient during training and the result shows that it improves walking ability and speed.

A locomotive control of a wearable lower exoskeleton for walking enhancement was presented in [22]. This system used an inner and outer exoskeleton to stabilize human walking ability while carrying a payload. The system muscular function improved on the power compensation but cannot automatically move the non-active leg. Hassan et al. proposed the feasibility of synergy-based exoskeleton robot control on inter-limb locomotion [23, 24]. This system generates a motion pattern from a non-paretic leg to aid assistance. The system was tested on patients and results showed an improved spatial symmetry ratio and more consistent step length.

An emerging area of neurorehabilitation is the use of robotic devices to enhance the efficiency and effectiveness of lower extremity physical therapy post-stroke [25]. The mobility training of post-stroke chronic patients using a bionic knee orthosis shows an improved gait speed of (10-m walk), stride length, and walking endurance (6-min walk). But the system cannot automatically move a paralytic leg. Since the mobile robot architecture must include sensing, planning, and locomotion which are tied together by a model.

In this research, a robotic wearable shoe that provides autonomous assistance to stroke patient with walking shoe impairment is develop and implemented for this common human disability using the approach of mechatronics and embedded system designed. This proposed robotic shoe system will align with the affected patient's legs locomotion automatically when the healthy foreleg of a human change in position. However, the application of wearable robotic shoe design includes support for the independent mobility of the elderly with muscle weakness, stroke patients, and people with impaired motor function as well as support for nursing care that involves heavy laborious work [26]. The remaining parts of the paper are arranged as Sect. 3 discussed materials and methods, Sect. 3.1 discussed modeling the architecture of hu-man-robotic joint alignments using linear control loop technique for the controller designed. Section 4 explained the hardware system design and implementation, Sect. 5 is results and discussion and Sect. 6 concludes the research with future re-search expectation.

3 Materials and Methods

The design of neuro-rehabilitation robotics wearable shoes for stroke patient locomotion assistance is proposed using the synergistic approach of combining closed-loop control of mechatronics with embedded system technology. The system model consists of software coding using C-language in the Arduino IDE and hardware system integrations. The hardware architecture for an intelligent robotic shoe impairment of human locomotion assistance includes sensing, planning, and locomotion which all are embedded in a single-on-chip controller system. The neuro-rehabilitation wearable robotic shoe prototype is designed and implemented to assist human disability locomotion as found in stroke patients. The workability principle and flowchart of the system (see Fig. 1).

3.1 A Modeling Architecture of Human-Robotic Joint Alignments

The human sensory part of the brain plays a significant role in motion that controls the arbitrary way of muscle movement Xd and serves as a feedback control-loop in the body system [27]. The motor control of the output signal is generated and sent to the muscle for joint torque F (see Fig. 2). The wearable robotic system can be achieved by

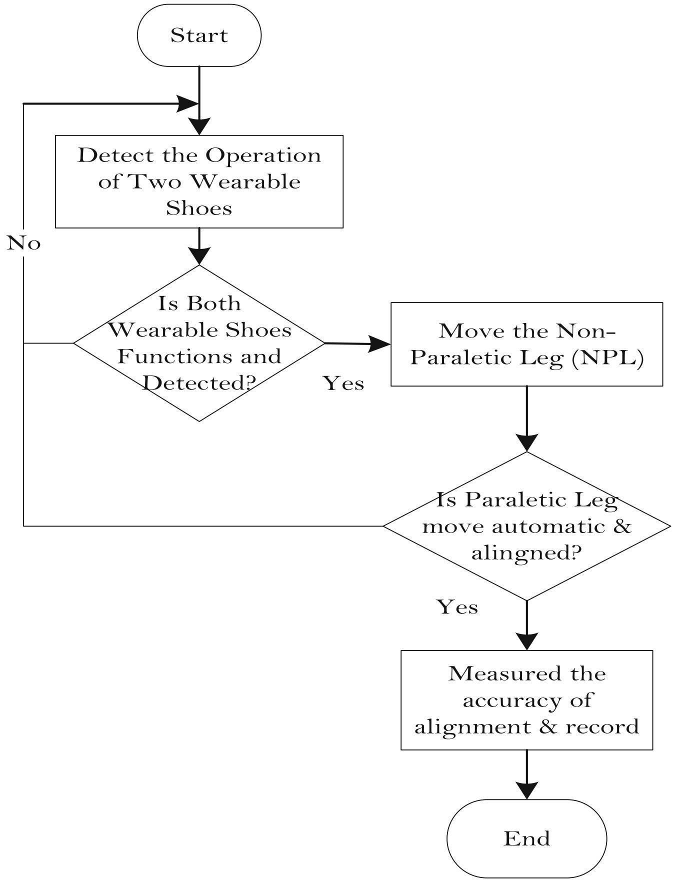

Fig. 1. The flowchart operation of wearable robotic shoes.

sending the received input signal from human motion (human-robot interface) through a muscular tissue (force sensors) and relay information to the embedded controller for the control (actuator). This signal will be processed to generate an assistance motion (torque Fa) to the muscle-skeletal body system accordingly [28, 29]. The closed-loop control system of the human wearable robotic locomotive system (see Fig. 3).

The impedance of the system can be expressed in the Laplace domain as the second-order transfer function *Z(s)* relating the net force *F(s)* to the position *X(s)* as given in Eq. (1). The parameters of *M, B*, and *K* denote the mass *(Kg)*, damping coefficient, and stiffness of the system respectively.

$$Z(s) = \frac{F(s)}{X(s)} = Ms^2 + Bs + K \tag{1}$$

In the control of the robot and actuator force *Fa(s)*, the actual dynamic behavior of the system can be modified and replaced by a set of virtual (or desired) parameters as *Md, Bd, and Kd.* This parameter form of control is referred to as the impedance or called admittance control. The acting force *F(s)* of the system is subject to the actuator effort *Fa(s)* generated by the motor. The admittance control can be used to adjust the actuator's force *Fa(s)* with different impedance as defined in Eq. (2). The parameters of *Md, Bd, and Kd* are the desired mass, damping coefficient, and stiffness.

$$Z_d(s) = M_d s^2 + B_d s + K_d \tag{2}$$

The measured position of *X(s)* is used as an input to an impedance control that contains the impedance parameters chosen in the form *Zd(s)*. This system control (impedance) produces the desired force *Fd(s)* as expressed in formula (3). The actuator force *Fd(s)* selected and the actual kinematic trajectory *X(s)* are purposely designed for robot control through the control inner force loop.

$$F_d(s) = \left(M_d s^2 + B_d s + K_d\right)[X_d(s) - X(s)] \tag{3}$$

Therefore, the design of a neurological impaired wearable robotic shoe system required an understanding of human motor control mechanisms [30] and related effects (injury). This is due to its principle of operation that is based on motion in the sagittal plane (front-to-back or back-to-front) through the center of the body [31]. An impedance control with adjustable parameters has been implemented for this assistive control system using derived formula in (4) and (5).

$$\tau = B(q)y + F_v q + F_s sign(q) \tag{4}$$

$$y = M_d^{-1}(M_d q_d + K_p q + K_d q \tag{5}$$

where τ is the torque command, B is the inertia matrix, $F_v q$ and $F_s sign(q)$ is the dynamic and static friction torques respectively.

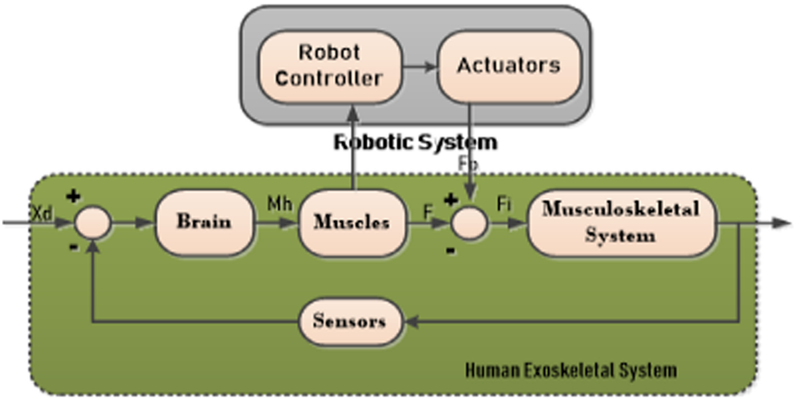

Fig. 2. The human-robot interaction control system.

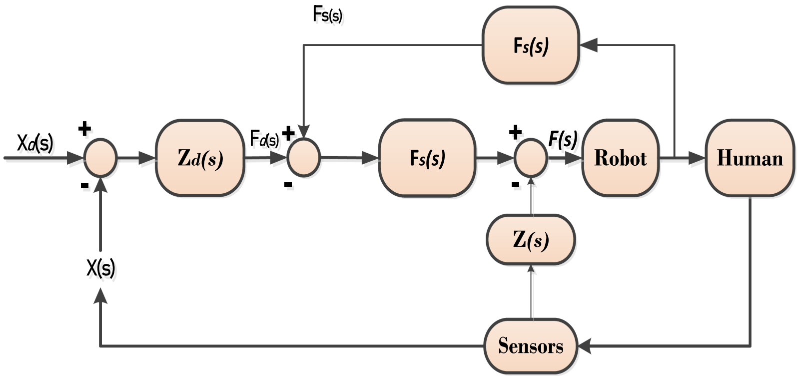

Fig. 3. The closed control loop impedance controller system.

3.2 Hardware System Design and Implementation of Human-Robotic Shoes

The robotic shoe system is a pair of footwear consisting of ultrasonic sensors (distance sensors), electric motors, tires, roller, microcontrollers, transceiver, power supply circuit, and some other electronic components. The (ATmega 328) is utilized as a microcontroller to process the input signal data sent to control the paralytic robotic shoe. The walking process depends on the paretic leg (robotic) to keep tracking and aligning with the non-paretic leg during human movement.

Power Supply Unit. The voltage supply of 5 V output is generated from the regulation of the 9 V battery (see Fig. 4). The positive terminal of the 9 V battery is connected to a switch in series while the negative terminal of the battery is grounded. The other terminal of the switch is connected to the input voltage (Vin) of the IC regulator (LM7805) and the output voltage (Vout) is then connected in parallel to a smoothening capacitor and LED as an indicator.

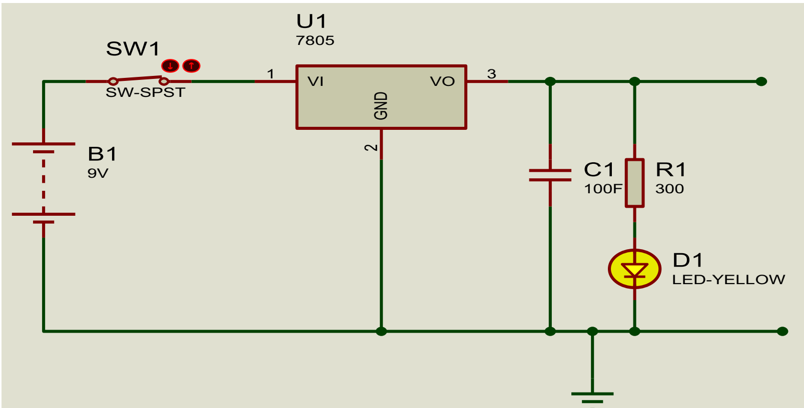

Fig. 4. A regulated power supply circuit diagram.

Position Awareness and Detection Unit. The ultrasonic distance sensor is implemented for non-contact distance measurement. It consists of a transmitter and receiver (Trigg and Echo) that are used to transmit and receive signals. The focus is to measure the time of flight of ultrasonic sound wave from the sensor to detect an object. Therefore, the distance between the transmitter and the object is calculated using simple computation by considering the time taken by the ultrasonic sensor wave to travel from the transmitter to the received end. The measurement range of the sensor is up to 20 m [32, 33] which continuously produces a sound wave that can reflect any surface material. The time it takes the wave to travels back from a reflector is related by the expression in (6) and (7).

$$T_{f(ref)} = D/k.V_s \tag{6}$$

if, $T_f \neq T_{f(ref)}$ then,

$$d = \begin{cases} V_m \times \tau \pm \varphi, T_f \neq T_{f(ref)} \\ 0, T_f = T_{f(ref)} \end{cases} \tag{7}$$

where, $T_{f(ref)}$ is reference time of an ultrasonic pulse to cover distance D in (m), V_s is the velocity of sound in air (m/s), K is constant close to 0.5 which depends on the sensor geometry, D is twice the distance between the legs, d is the distance to be covered by the motor for alignment in (m), T_f is the time of flight when the legs are not aligned, V_m is the velocity of a motor in (m/s), ϕ is the adjustment constant.

Therefore, the navigation is introduced to maintain the distance between the legs and position, thus D is kept constant within range as in formula (8).

$$V_N = {}^{D}\!/_{T_f} \tag{8}$$

Since the ultrasonic sensor has four pins which are trigger (*Trig),* echo, power *(Vcc), and ground (GND)* port. The Vcc is connected to the 5 V supply, Trig, and echo ports are connected to the microcontroller pins, and the ground is connected to the 0 V. Thus, the distance between the legs can be estimated and the absence of one leg can be detected.

Communication Module. The radio frequency (RF) transceiver is operating at 433 MHz with a data speed of 10 Kbps and is used to establish communication between the pair of robotic shoes. The ultrasonic sensor and the transceiver input signal are processed by a microcontroller to send a command to the dc electric motors. This transmitter utilizes the radio wave link to transmit signals in the form of radiofrequency. The communication distance range depends on the voltage input of (3.5–5 V) of the transmitter. The higher the power input the higher the range but the shorter the life span of the battery. Therefore, the supply voltage of the 0.7 V signal diode is connected in series with the 5V to limit the input power of the transmitter to 4.3 V.

Locomotive System Unit. The two pairs of mini-tires are connected to a pair of 5 V DC-motors with a no-load speed of 200 revolutions/minutes, load-speed of 152 revolutions/min, and torque of 1.0 Kg.cm output which in turn connected to ULN2830. The ULN2830 is connected to four pins of the Microcontroller to transmit and receive commands and is powered by a 5 V power supply. The locomotive circuit design of the wearable robotic system (see Fig. 5 and 6).

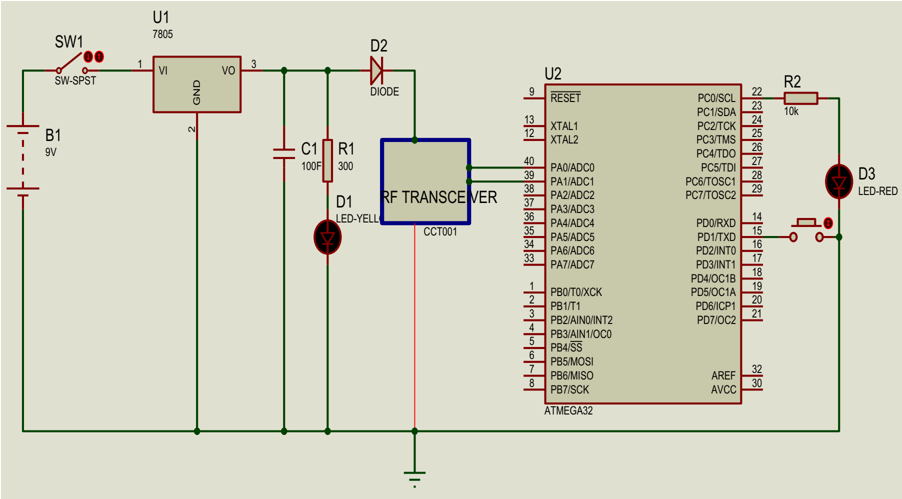

Fig. 5. A circuit design for non-paralytic robotic shoe.

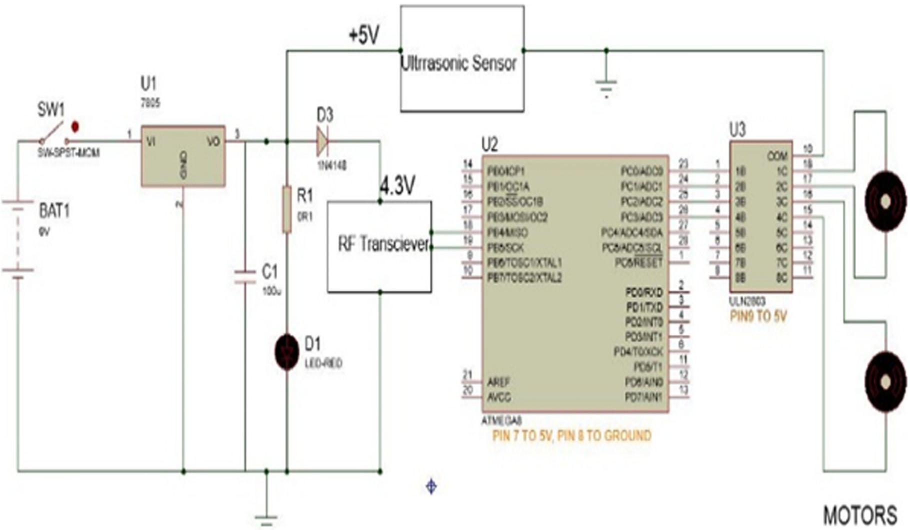

Fig. 6. A circuit design for paralytic robotic shoe.

4 Results and Discussion

The neuro-rehabilitation wearable robotic shoe prototype is designed and implement-ed to assist human disability locomotion as found in stroke patients. This system is tested by observed the position of the non-paretic leg (NPL). Whenever this NPL is lifted or move from point A, then the paretic leg (PL) at position B will automatically sense the change in position A and move to align with it. This process continues the same way to assist the stroke patients in moving the paretic leg automatically (see Fig. 7). The alignment accuracy of the system was tested and recorded during movement at a distance of (10, 20, 30, 40, and 50) meters apart. The result is presented in Table 1, and Table II contains error occurrence at different distances of locomotion.

Fig. 7. A design prototype for the robotic wearable shoe.

The horizontal distance between the two legs is W, the forward distance move by the non-paretic leg and the paretic leg are DNPL and DPL respectively. During the movement, we observed differences at 15 cm distance apart between the legs W, while the non-paretic leg has moved a distance of 10 cm, the paretic leg tracked and aligned with a difference of 0.05 cm. Also, at the same distance apart, while the non-paretic leg has moved a distance of 20 cm, the paretic leg aligned with 0.06 cm error as contained in Table 1.

Table 1. Alignment accuracy of a wearable robotic shoes testing.

W = 15 cm		W = 20 cm	W = 25 cm
D_{NPL}(cm)	D_{PL} (cm)	D_{PL} (cm)	D_{PL} (cm)
10	9.95	9.95	9.94
20	19.94	19.94	19.94
30	29.92	29.91	29.90
40	39.92	30.90	39.85
50	49.90	49.90	49.85

4.1 System Performance Evaluation

The performance of this system is evaluated based on the alignment metric using the correlation coefficient between two wearable robotic shoes. The correlation coefficient is

Table 2. Error differences in the locomotive alignment testing.

Distance D_{NPL}(cm)	10	20	30	40	50
Error (e)	0.05	0.06	0.08	0.08	0.10

the statistical measurement that determines the relationship between the relative movements of the two variables. The correlation coefficient value ranges from −1.0 to 1.0, while a value of 0.0 is coefficients denotes no relationship between two variables. The alignment correlation coefficient is determined using the expression in (9).

$$p = \frac{Cov(D_{NPL}, D_{PL})}{\sigma_{NPL}\sigma_{PL}} \tag{9}$$

where $Cov(D_{NPL}, D_{PL})$ is the covariance of the two legs while $\sigma_{NPL} and \sigma_{PL}$ is the standard deviation of the individual legs. If our linear model characteristics is (10), the uncertainty measurement for the regression coefficient (μ) can be determined as in (11) and (12).

$$\gamma = \alpha_0 + \alpha_1.\beta \tag{10}$$

$$\mu^2(\alpha_1) = \frac{n}{n\sum_{i=1}^{n}\beta_i^2 - (\sum_{i=1}^{n}\beta_i^2)^2}.\sigma^2 \tag{11}$$

$$\mu^2(\alpha_0) = \frac{\sum_{i=1}^{n}\beta_i^2}{n\sum_{i=1}^{n}\beta_i^2 - (\sum_{i=1}^{n}\beta_i^2)^2}.\sigma^2 \tag{12}$$

The covariance $cov(\alpha_0, \alpha_1)$ between the regression coefficients estimation is (13), and the standard deviation σ of distance (γ_i) can be estimated with residual variance is (14).

$$\mu(\alpha_0, \alpha_1) = cov(\alpha_0, \alpha_1)\frac{-\sum_{i=1}^{n}\beta_i}{n\sum_{i=1}^{n}\beta_i^2 - (\sum_{i=1}^{n}\beta_i^2)^2}.\sigma^2 \tag{13}$$

$$\sigma^2 MSE = \frac{1}{n - 2\sum_{i=1}^{n}[w_i - (\alpha_1.\beta + \alpha_0)]} \tag{14}$$

The alignment accuracy was conducted and the results are presented (see Fig. 10, 11 and 12). The error difference in alignment testing results in a positive correlation between the two legs (see Fig. 13).

4.2 Evaluation Analysis

The testing of the experimental robotic wearable pair of shoes for the human/patient locomotive disability assistance system was measured and the performances are evaluated using the correlation coefficient to determine the error occurrence during ambulation. At a distance of 10, 20, 30, 40, and 50 m covered during ambulation testing, the error

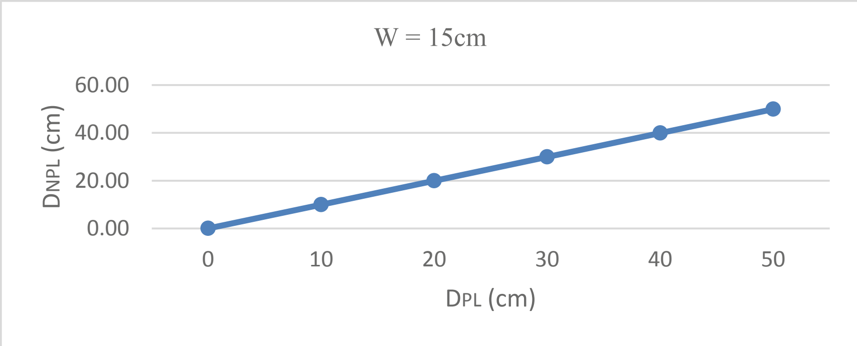

Fig. 8. A relationship between NPL and PL Alignment at W = 15 cm.

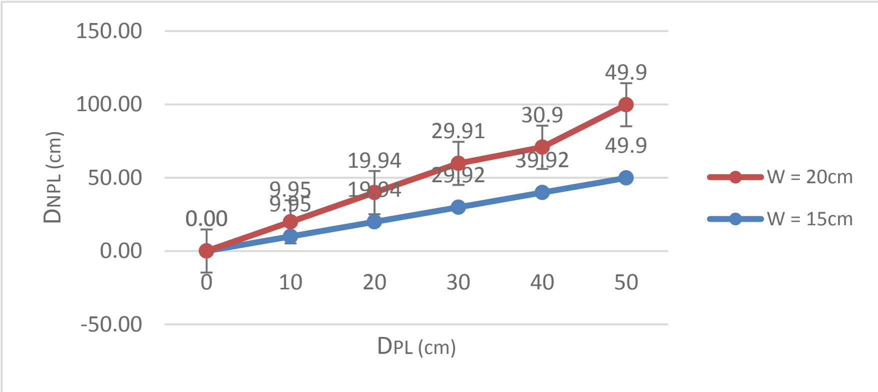

Fig. 9. A relationship between NPL and PL Alignment at W = 15 and 20 cm.

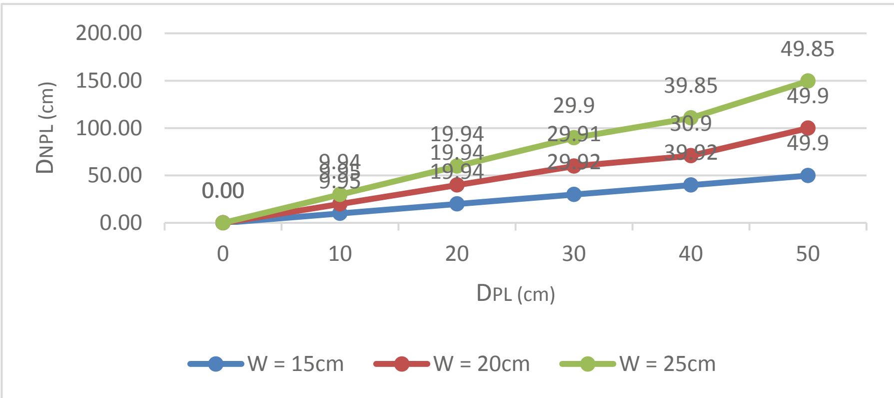

Fig. 10. A relationship between NPL and PL Alignment at W = 15, 20 and 25 cm.

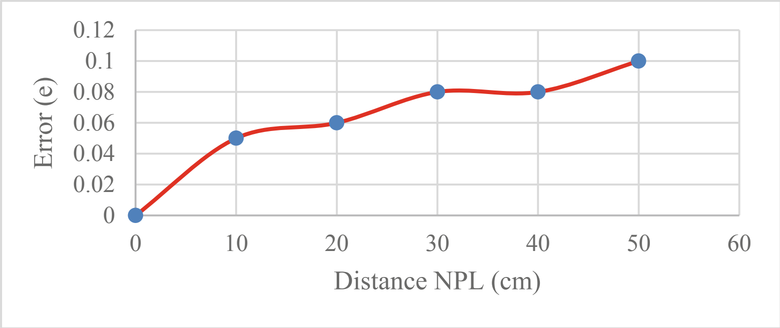

Fig. 11. Error relationship between NPL and PL alignment.

occurrences in the gait alignment of the shoes were observed and recorded as 0.05, 0.06, 0.08, 0.08, and 0.1 respectively. The average error recorded over the ambulation of 50 m traveling was recorded as 0.236. Therefore, the robotic pair of shoes response (latency) to communication was fast and prove the efficient performance of the system through the application of closed-loop control theory of the mechatronics and embedded system techniques. The performance evaluation of the system was not benchmark with any existing work because of the different researcher's opinion and focuses in the neurorehabilitation of wearable robot for lower-limb weaknesses. Also, the performance metrics used was stated as in [21–24].

5 Conclusion

The stroke patient locomotion assistance system prototype was designed and implemented. This system was tested and observing that it is working effectively with mi-nor correlation errors in the pair of shoe alignment. The result shows its efficiency and workability to assist stroke patients' disability to walk linearly and limit the humanitarian assistance for locomotion likewise help in exercising the legs. Therefore, the industrial realization design of this system will require the hi-tech and sophisticated implementation of sensors, intelligent controllers with fuzzy applications, actuators, and many others. This is to achieve an efficient performance of the system with fewer errors. The alignment of both paralytic and non-paralytic legs is measured at 10 cm apart with a 0.05 cm difference, while at 20 cm distance has 0.06 cm differences in position. However, this robotic wearable pair of the shoe helps the stroke patient with a paralytic leg in ease of locomotion and other people with lower limb disability. It will also help improving balance and support the heel of the patient for easy movement and to maintain balance. Future research work will focus on molding and design of a full-bodied wearable robotic pair of shoes using the Laplace domain of control theory and force localization estimation for detection of a prosthesis in motion using an artificial neural network (ANN).

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