Design and Preliminary Testing of an Instrumented Exoskeleton for Walking Gait Measurement

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***Abstract*—This paper presents the design and preliminary testing of an instrumented exoskeleton system, which is targeted at collecting gait data of the human locomotion to support the controller development of lower-limb wearable robots. This compact and lightweight device features a unique two-degree-of-freedom joint to minimize the interference to the user movement and a simple yet effective adjustment mechanism to fit subjects at different heights. For the gait measurement, the device incorporates embedded joint goniometers to obtain the knee and ankle positions, and inertial measurement units to obtain three-dimensional kinematic information. Force-sensing resistors are also incorporated into the shoe insole for plantar pressure measurement. Sensor signals are routed to an onboard microcontroller system for data storage and transfer, and the system is fully self-contained with onboard battery to facilitate data collection in various environments. A prototype of the exoskeleton was fabricated, and preliminary testing was conducted on two healthy subjects in various postures and modes of movement (walking, sitting, standing, stair climbing, etc.). The evaluation of a temporal event detection test showed no more than 5.5% mean variation in the measure of step counts by the sensory system and video annotation. These results indicate that the exoskeleton can provide an accurate measurement of gait information, using measurements taken from external video recordings as the benchmark in this preliminary validation study.**

***Keywords*—exoskeleton, wearable sensors, prosthesis orthosis, gait measurement**

I. Introduction

Wearable sensors have been developed for the acquisition of kinematic trajectories of the human body, utilizing a variety of instrumentation and body-mounted framework [1]–[4]. Body-worn sensors offer an alternative to traditional optical motion capture technologies, the use of which can be prohibitive due to the need for a dedicated facility [5]–[8]. Due to these constraints, the body-mounted framework can restrict the possible kinematic information gathered to motions that can be performed in the laboratory setting.

Measuring gait kinematics with wearable sensors has its advantages, among the foremost of which is portability, although there are several challenges in the design of such a device. To achieve accurate measurements, a wearable device must be yielding enough to pose no restriction to the user's natural motion, yet rigid enough to ensure certain sensors are not displaced relative to the user's body.

One method of addressing this challenge is the use of lower-limb as a body-mounted framework for sensory instrumentation [9]. This has served as a basis for several designs with a variety of applications, further discussed in the following section. The simultaneous implementation of multiple sensors assists in the measurement of precise movements and reducing the effect of false positives in walking event detection by an individual sensor. A robust sensor array can also provide an informational basis for intent recognition of human motion [10], [11], enabling the refinement of a lower-limb assistive device controller. However, the design of a supporting exoskeleton system demands specific human characteristics such as ergonomics and wearability; a global design targeting users of all morphologies or limb sizes and allowing unrestricted natural motion is necessary.

Motivated by these factors, a wearable exoskeleton system was developed in this study to: ensure a comfortable, portable user interface for a variety of limb sizes without restricting the natural range of motion of the user; obtain minimally intrusive measurement of gait kinematics from multi-sensor signals; and store time-synchronized sensor signals to support later development of a personalized prosthesis controller for automatic motion-intent recognition and controller tuning.

The scope of this research encompasses both mechanical and electronic design and experimenting with healthy individuals. The mechanical design covers modeling the fabrication of the exoskeleton; the electronic design includes the development of a microcontroller-based data acquisition framework to capture sensor signals; the laboratory testing covers the implementation of the exoskeleton system on two volunteers, capturing locomotion data and evaluating sensor signals. This system was proven to have minimal set-up or calibration procedures, no subject specific-alignment of sensor-joint axis alignments, using a lightweight, cost-effective design.

The paper is organized as follows. Section II discusses related work in lower-limb mounted instrumentation framework. Section III presents detailed system methodologies: mechanical and electronic components, sensor placement, firmware, and validation procedures. Validation results are provided in Section IV. Section V evaluates these results, exploring possible applications of the system, and discusses future work and conclusions.

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II. Related Work

Lower-limb instrumentation has been used in various designs, and is capable of supporting a diverse amount of sensors to suit the application. For instance, inertial measurement units and potentiometers were employed in the Hybrid Assistive Limb exoskeleton to measure joint angles [12], and similarly, rotary potentiometers were used in an MIT exoskeleton to measure hip and knee angles [13]. Joint angle data has also been measured through the use of magnetic encoders [14] and fiber-optic goniometers [15], [16]. In addition to kinematics, wearable instrumentation has been used to acquire gait kinetics by employing force plates [17] and force-sensing resistors [3].

Electromyography (EMG) has also been employed in lower-limb instrumentation to detect muscular activity for gait analysis [18]. Of particular relevance to this paper, the LOPES exoskeleton robot developed by Veneman *et al.* is a powered gait rehabilitation device which uses electromyography to guide or assist walking, and was used to explore the feasibility of acquiring inverse-dynamics gait measurements from the EMG data while walking unhindered [19]. However, measurements in the prototype evaluation indicated insufficient accuracy for inverse dynamic calculations.

Hassan *et al.* designed a similarly pertinent wearable sensor system for the control of Robot Suit HAL, also a powered gait rehabilitation exoskeleton, which implemented an instrumented cane alongside lower-limb wearable sensors for motion intent estimation and control [20]. Intended for hemiplegic users, the instrumented cane provided upper-limb data to fuse with sensors on the lower limb to control the exoskeleton on the contralateral limb.

III. Methodologies

A. Mechanical Design

The mechanical structure of the instrumented exoskeleton consists of three segments, including a thigh segment, a shank segment, and a foot segment. These segments are connected by two instrumented joints to measure the movement of the corresponding biological joints (Fig. 1). The primary objectives in the design include reducing device weight, generating a compact profile, and providing a comfortable user interface to minimize the interference with the user movement while supporting a sensor array for accurate lower-limb motion capture.

In order to reflect the range of motion of the knee and ankle about both the sagittal and frontal plane, an additional degree of freedom was incorporated into the joint design, allowing for unrestricted movements in the frontal plane without interfering with the measurement of the joint sensor.

A thin (5 millimeter thickness) aluminum bar establishes a linkage between two joints. Its shape can be adjusted to align with the user's calf curvature using orthotic bending irons. The connectors between the aluminum bar and either joint provide a measure of height adjustability (Fig. 2) with a range of approximately 7.6 cm. This simple yet effective adjustment mechanism enables the device to fit subjects at different heights in a configuration that ensures the joint sensor is fixed on-axis with the rotation of the measured joint.

Fig. 1. Exploded view of 2-Degree-of-Freedom (DOF) joints of the Measurement exoskeleton system (developed for right leg)

For the joint sensor to reliably measure the angle of the corresponding joint, it must remain aligned with the central point of rotation. Given the curvature of the thigh and calf, however, the device may misalign after repetitive motion. To address this issue, two aluminum bands for the thigh and the calf were incorporated along with webbing straps coupled with tri-glide slides and buckles, ensuring minimal sensor shift relative to the user's body. The shape of the thigh/calf band can also be adjusted to fit users with different limb sizes using orthotic bending irons.

The ankle joint was attached with a carbon fiber foot segment embedded beneath the user's shoe sole, providing a fixed frame of reference to measure the angular position of the ankle joint.

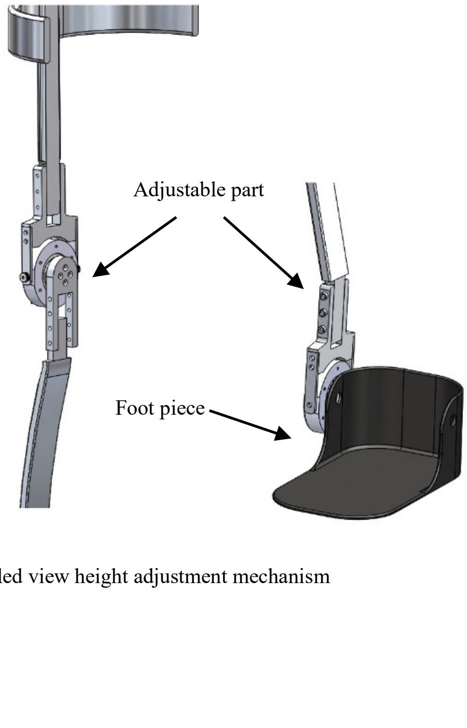

Fig. 2. Detailed view height adjustment mechanism

B. Sensing Elements

The exoskeleton system consists of a set of sensors and data acquisition electronics with a 3.7 V Li-polymer battery of 300 mAh capacity. This system employed STM32L476RG, a Cortex-M4 Ultra-low-power ARM processor (ST Microelectronics, Geneva, Switzerland) with an 80 MHz CPU at 39 µA/MHz; a 16GB micro-SD card to store data sampled at 1 kHz by the MCU (microcontroller); and a micro-USB interface to control data collection, access sensor signals stored in the SD card, update MCU timestamp, recharge the battery, and upload firmware.

The sensor suite was capable of monitoring accelerations in all three directions, rotations around each axis and absolute directions; changes in a two-pole magnet's angular position in the associated magnetic field of a rotary encoder; and change in resistance upon applying pressure or mechanical stress. The motion tracking was performed by three 9-axis IMUs, MPU-9250 (InvenSense Inc, San Jose, CA), which combines a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer. The accelerometer, gyroscope, and magnetometer of all three modules were configured to have a ±8g, ±2000dps, and ±4800µT measurement range, respectively, with 16 bits of resolution. These IMUs were interfaced with the MCU through three SPI interfaces.

The contactless magnetic rotary encoder, AS5145 (ams AG, Unterpremstätten, Austria), can measure acute angles over a full turn of 360 degrees with 14 bits of resolution. Two magnetic encoders were interfaced with the MCU through two serial synchronous interfaces, a typical serial interface between an absolute position sensor and a controller.

The polymer thick film FSR (Force Sensing Resistor) is capable of measuring pressure utilizing its property of decreasing resistance with the increase in the applied force on its active surface. The FSR 406 (Interlink Electronics, Camarillo, USA) has a 39.6 mm square active area. Protective plastic sheaths were placed around two FSRs with a layer of insulating tape and embedded into a shoe insole. A resistive divider was formed by each FSR and a 500Ω resistor and applied to op-amp based voltage followers. Op-amp output of FSRs was interfaced to two ADC channels of the MCU (with 12 bits of resolution).

C. Sensor Placements

Three IMUs of the data acquisition system were placed in different parts of the body to effectively perceive the movement information. One IMU was placed on top of the waist belt using a Velcro strap. The trunk IMU was worn as a pendant below the neck beneath clothing to indicate the overall movement and inclination of the upper body. Another IMU was mounted on the acquisition circuit which was mounted in a lateral position below the knee joint. All IMUs were positioned at a configuration to have the y-axis perpendicular to the ground, the x-axis parallel to ground toward body movements and the z-axis away from the body (illustrated in Fig. 3). The rotary magnetic encoders were placed in the 2-DOF joints to measure the angular position of the knee and ankle. FSRs embedded under the shoe sole were installed at the main force points to measure heel and ball pressures under the foot.

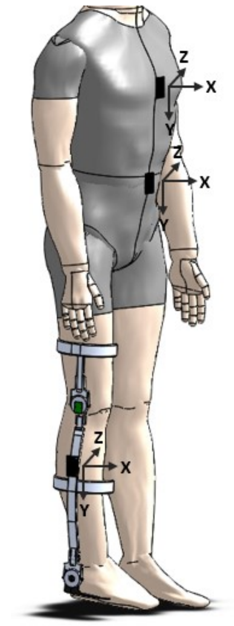

Fig. 3. An illustration of IMU placement with skeleton system

D. Embedded Software

Development of the data acquisition firmware started with defining four major states of the system: a) Active Data Collection Mode, b) USB (to PC) Communication Mode, c) Low Power Deep Sleep Mode, d) Low Battery Alert Mode. For the active mode, the microcontroller clock was set as 80 MHz considering the high sampling rate (1 KHz) of sensors. A double buffer scheme (each buffer 16 KB) was adopted during data collection to read the current sensor values in one buffer while simultaneously storing the content of the previous buffer in a binary (.BIN) file of the SD memory. The micro-SD card was configured to store a sensor buffer in every 0.26 seconds, the time required to fill one buffer. The USB interface of the system was configured as the VCP (Virtual COM Port) mode to exchange commands from users to control sensor activities and synchronize device time to an internet time server through a developed computer application; access sensor files (MSC-Mass Storage mode); or update system firmware (DFU- Device Firmware Upgrade mode). During the low power deep sleep mode, the processor clock was stopped, and all sensor modules were configured to be their low power modes to limit the power consumption to the lowest possible value. A battery level monitoring system was also configured which continuously checks the battery voltage level. If the battery decreases to the lowest threshold level during data collection, or even in the low power deep sleep mode, the system will gracefully shut down all modules and generate an alert for the user attention.

E. System Validation

The validation of system modules was performed in two steps. First, in the bench test, statistical characterization of system (inherent) noise was performed by evaluating the device response while the system remained idle on a flat wooden surface without magnetic interference. Statistical measurements for sensor noise (such as the mean and standard deviation of noise) were also computed. Second, in a laboratory setting, the collection of samples from healthy individuals were performed and the suitability of the system was evaluated. Two volunteers having age, height, and the weight of 31 and 27 years, 1.72 and 1.77 meters, 172 and 160 pounds, respectively, with no physical and cognitive abnormalities, participated in this test. The study was approved by the Institutional Review Board (IRB) at the University of Alabama. With the exoskeleton applied, they performed following activities: a) sitting, b) standing upright, c) level treadmill walking in four incremental speeds: 1mph to 4mph, d) inclined treadmill walking with 10° inclination in three incremental speeds: 1mph to 3mph, e) natural ground walking in self-selected moderate and fast cadence, f) stair ascent and descent, g) elevator climbing, h) repeated sit-to-stand-to-sit transitions, and i) self-selected walking with fixed change of direction. All these individual activities had a maximum duration of 1 min. The entire laboratory session was videotaped by an iON contour video camera at 60 fps capture rate. In a smartphone application (aTimeLogger—Time Tracker), the start-end timestamp of each activity were marked. Both the camera and the smartphone were time-synchronized with the exoskeleton by sending the same internet timestamp to all three devices. After completion of the session, volunteers were asked to provide feedback on the acceptability of the exoskeleton system in terms of longer-term usage and effect on mobility.

F. Signal Processing and Data Analysis

The recorded sensor signals were first processed by a developed MATLAB script for noise removal. A second-order low pass Butterworth filter with an empirically selected cutoff frequency of 10 Hz was applied to individual sensor signals. De-noised sensor signals of the entire study period were plotted in the same scale and inspected for the presence of spurious segments. Fig. 4 illustrates an instance of sensor responses while a volunteer was walking at a slow pace over the ground. To validate the responses of magnetic encoders, the pattern of the displacement angle of knee and ankle was compared with a standard biomechanical walking signal provided in literatures [21], [22]. To validate the pressure sensor and IMU responses, the number of steps were computed (using MATLAB's findpeaks algorithm) over all walking activities and compared with counts obtained from the video. For IMUs, vertical and forward (toward motion) accelerations were only considered following the study [23] which showed that walking steps measured from the changes of vertical and forward acceleration are strongly correlated to the walking speeds.

IV. RESULTS

The system noise measurements obtained from the idle bench test are summarized in Table I. The comparison of displacement angle measurements by exoskeleton magnetic encoders and the reference biomechanical signal is presented in Fig. 5. Pressure sensor and IMU validation results are provided in Table II which confirms no more than 5.5% mean variation in step counts by the sensor system and video. Volunteers also reported the system to be lightweight and comfortable enough to be applied for long time periods without interfering with natural movement.

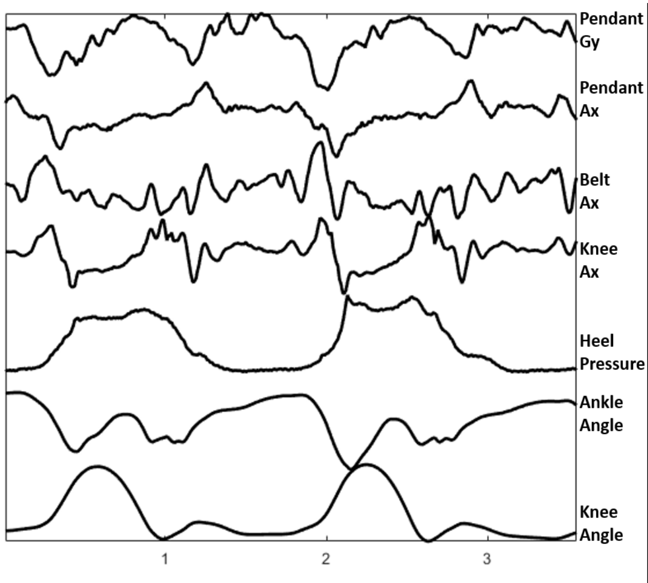

Fig. 4. The response of exoskeleton sensors while a volunteer was walking over ground.

TABLE I. IDLE TEST NOISE CHARACTERIZATION RESULTS

Sensing Element	Noise Mean Value	Noise Std. Deviation
Knee Magnetic Encoder	0.2 Degree	0.07 Degree
Ankle Magnetic Encoder	0.3 Degree	0.05 Degree
Heel Pressure Sensor	12.24 mV	1.21 mV
Stride Pressure Sensor	9.24 mV	1.87 mV
Knee Accelerometer	0.05 g	0.007 g
Knee Gyroscope	2 dps	1.2dps
Knee Magnetometer	1uT	0.02uT
Belt Accelerometer	0.02 g	0.003 g
Belt Gyroscope	1 dps	0.3dps
Belt Magnetometer	1.2uT	0.05uT
Pendant Accelerometer	0.06 g	0.009 g
Pendant Gyroscope	1 dps	0.2dps
Pendant Magnetometer	1.4uT	0.06uT

TABLE II. A COMPARISON OF STEP COUNTS (30 SECONDS) OBTAINED FROM EXOSKELETON SENSORS AND MANUAL VIDEO OBSERVATION

	Pressure Sensor	Knee IMU 1D Data	Belt IMU 1D Data	Trunk IMU 1D Data	Manual Count
Walk 1mph Treadmill	23	23	23	21	23
Walk 2mph Treadmill	33	32	31	31	33
Walk 3mph Treadmill	32	31	27	30	32
Walk 4mph Treadmill	39	41	37	39	39
Ground Walking	21	22	21	21	21
Inclined Walk 1mph Treadmill	32	31	32	31	32
Inclined Walk 2mph Treadmill	25	25	22	24	25
Inclined Walk 3mph Treadmill	30	30	29	28	30

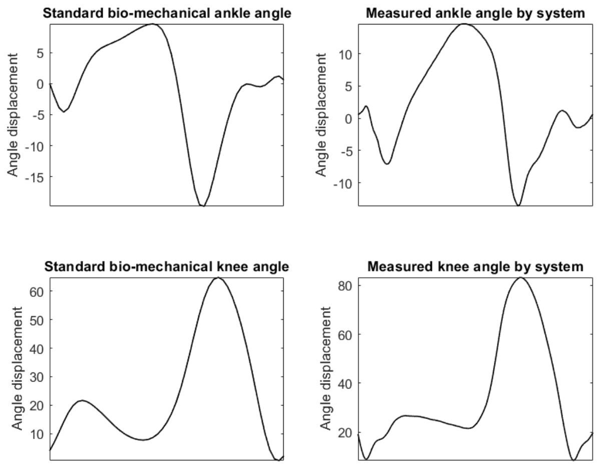

Fig. 5. A comparison of ankle and knee displacement angles measured by the exoskeleton system and standard biomechanical walking signal.

V. Discussion and Conclusion

The goal of this study was to develop a durable but lightweight exoskeleton system to gather objective lower-limb biomechanical information of the wearer. The 2-DOF joints were developed, which enable the knee and the ankle movement in the frontal plane and significantly improves the comfort in wearing. The adjustable components facilitate use of the device by a variety of user sizes.

Sensors of this system were low cost, low power and capable of providing data in unrestricted environments. These sensors can provide information on the wearer's current position and movement from knee and torso motion and rotations, body-joint angles and their angular velocities, distribution of plantar pressure of the foot and ground reaction force. The data provided by multiple sensors can also be used in the development of accurate detection algorithms for motion intent recognition. The belt and pendant IMUs implemented in this system provide the option of modular implementation on suitable body locations demanded by the application.

The bench test showed that sensor modules contain a negligible amount of noise which did not impact overall performances of the system. The walking sequence obtained from magnetic encoders matches with the reference biomechanical signals provided in the literature. Point to point comparison was not feasible here as signals were captured from two different persons under different settings. The validation of step count temporal event also justifies general system responses. One limitation of system testing was the lack of comparison with a concurrent 3D motion analysis system, which would have allowed for more rigorous validation.

The proposed study was a proof-of-concept with healthy volunteers to evaluate the extent the wearable sensors could be used and the wearability in terms of comfort and mobility. The volunteers were comfortable self-applying the device onto their lower limb and responded positively to the possibility of extended use. The multi-sensory system was developed over a commercial MCU development board which would be downscaled to a small PCB with a reduced wired connection for final application. Beyond the camera and timer annotation employed in this study, other reference systems may be added to the setup for critical motion analysis. The MCU of the exoskeleton has an internal clock which maintains time-synchronization among all sensors. The stored sensor signals in the SD card also contain the MCU timestamp to facilitate any further annotation from additional sources.

The successful testing of the exoskeleton system on two volunteers suggests possible implementation in prostheses responding to the intention of the wearer. However, this is limited by the sampling of only two subjects. To further pursue this, performance evaluation with varying body sizes and gait patterns is necessary, requiring both a larger sample size and testing on disabled and elderly subjects. The foreseen potential use of this exoskeleton system is primarily the development of a personalized adaptive controller for auto-tuning regulator parameters. The exoskeleton system itself can also be served as a platform for testing these control methods. Also, this system may be used in the real-time locomotion control of a bipedal humanoid robot.

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