Approval Sheet

The Design Research Seminar Project titled “A low cost wearable device for visualizing altered gate patterns from different footware” by Enlin Quental (Roll Number 176330007) is approved for partial fulfillment of the requirement for the degree of ‘Masters in Design’ in Interaction Design at the Industrial Design Centre, Indian Institute of Technology, Bombay.

Supervisor

A Low-Cost Wearable Device for Visualizing Altered Gait Patterns from Different Footwear

Visualizing the Changes in Gait Pattern and Events from Different Footwear Used

ABSTRACT

Footwear of a particular type has to be worn for the activity it is designed for. Wearing ill-fitting footwear leads to blisters, injury and altered gait patterns. Capturing and visualizing gait patterns has been used by researchers for testing the reliability of different gait capturing sensors; by doctors and physiotherapists for early identification of pathological gait, and rehabilitation; by footwear companies, physical trainers and coaches for preventing injuries in joints and muscles, and for improving the physical and technique in professional players. There are many articles on the effects of high heeled and ill-fitting footwear have been written in health websites and magazines, but there is no visual data on the variations of the altered gait patterns. It is expensive to visually analyze the changes in the gait pattern using gold standard devices. One of the methods for detecting gait events is through an Inertial Measurement Unit (IMU) sensor. It is a cheap, reliable and portable sensor when compared to other devices for capturing gait data. In this paper, we discuss the initial development of a gait sensing device and a tool to visualize the changes in the gait pattern when different footwear were used; the preliminary user evaluation of this device, and the analysis. Our evaluation shows that all the participants reported the visualized data of the gait patterns was informative, their footwear caused alterations in their gait pattern and they will be considering a comfortable footwear so as to maintain their normal barefoot walking gait pattern.

CCS CONCEPTS

• H.5 Information interfaces and presentation

• H.5.1 Multimedia Information Systems

DOI: https://doi.org/10.1145/3290605.XXXXXXX

KEYWORDS

Data Visualization; Gait; IMU; Footwear; Wearable Device; Wireless sensing

INTRODUCTION

A proper fitting and good quality footwear gives comfort and prevents possible pain, injury, and blisters. Ill-fitting footwear can lead to biomechanical imbalance, which can further cause foot problems, discomfort, pain, blister, and corn [16]. Study reported that foot problems as well as footwear deformation occurred in higher percentage in the right than in the left foot [16]. One possible reason behind this could be due to the gait. This same study also showed that women had more foot problems than men. The footwear and the type of footwear, especially when a heeled footwear was worn, would affect the gait with respect to the horizontal ground reaction forces and the orientation of various limb segments, step length, stride length and cadence [20]. These causes depends on the design of the footwear and the experience of the person wearing that type of footwear. It was also observed that shoe ground contact area decreased with increased lateral stability and heel height [14].

In their seminal paper R. W. Soames and A. A. Evans mention several factors affecting gait [14]. They prove “types of footwear causes different gait patterns”. “Studies have shown changes in pedal pressure patterns as a result of wearing shoes compared with walking barefoot [14]. The effects of high heels on ankle and knee joint angles were investigated by Gollnick, who observed an increase in ankle plantarflexion of some 20" throughout the gait cycle when high-heeled shoes were worn, but found only minor changes in knee angles under the same conditions [14]. Murray has observed differences in the total range of ankle movement during the wearing of shoes of different heel heights, with the range of movement being smaller with higher-heeled shoes [14]. In addition, the pattern of ankle movements in high heels showed a less pronounced plantarflexion-wave at the end of stance phase. Joseph stated that in spite of these modifications to the patterns of angular changes, relatively few differences in muscle activity have been observed between wearing low-heeled and high-heeled shoes, the main differences being in the activity of the tibiaIis anterior, soleus and quadriceps femoris muscles [14]. It would appear that high-heeled shoes bring about a changed loading configuration in the foot, and with it problems of stability and balance. According to Adrian and Karpovich and Merrifield, walking in heels causes a significant decrease in step length, in out-toeing and in the total range of movement at the subtalar joint [14]. These authors also observed greater instability during the support phase of walking in shoes with high heels in 60% of subjects studied. It would appear therefore that wearing shoes modifies not only the pressure patterns under the foot during gait, but also the nature of the impulsive load imparted to the skeleton at heel strike. The wearing of shoes has been shown to change the way in which the foot is used during gait, not only with respect to pedal pressure patterns but also in the temporal relationships of foot contact during the stance phase [14]. Whether there are such modifications in the gait patterns of men is debatable, since men tend to wear flat-heeled shoes, the major differences in men's footwear being in the rigidity of the sole. In the working environment perhaps the most useful suggestion that can be made is that floor surfaces should not be smooth, but should provide a high degree of friction to provide an environment to promote natural walking. Conversely, of course, the soles of all shoes could be corrugated, but that is highly unlikely in our fashion-conscious society [14]. "

In 1984, Howard and Okley; and in 1998, Rosenblad-Wallin Else, had recommended that "lighter, softer and more flexible footwear might give better fit, mobility and climatic effort, to design the military footwear." Therefore a footwear should be designed with proper care and fitting for each individual and demographically or for small population wise [16], because foot volume of people varies across places, and foot volume for both the legs are not symmetrical—which means the foot volume are different for both foot of an individual. Thereby reducing many orthopedic, joint and muscle injuries, and other foot problems [16].

Gait analysis could also point on the potential diseases or abnormalities in advance [18] [23]. Table 1 shows the typical causes of gait deviations [2]. Table 2 shows area of application of gait analysis and how much of the related parameters are used in each applications [23]. In the area of running sports, studies showed that "independent of the skill level, heel lift decreased during the course of the run due to progressive muscle fatigue [26]".

Table 1: Patient population associated with gait deviations

Category	Diagnosis
Cerebral palsy	Congenital brain anomaly Hemiplegia Hereditary spastic paraplegia Monoplegia Spastic diplegia with or without ataxia Spastic quadriplegia with or without athetosis Spastic triplegia
Other neuromuscular conditions	Beckers muscular dystrophy Congenital muscular myopathy Duchenne muscular dystrophy Spinal muscular atrophy Peripheral neuropathy Charcot-Marie-Tooth Cerebellar ataxia Central dystonia Myelodysplasia Myelomeningocele/spina bifida Brain or spinal cord injury or tumor Lower motor neuron injury Neuromuscular condition of unknown origin
Rotational deformities	Femoral or tibial torsion (external or internal) Miserable malalignment (both femoral and tibial torsion)
Angular deformities	Genu valgum (knock knees) or varum (bow legs) Blount disease Rickets
Foot deformities	Cavovarus or cavus foot deformity Drop foot deformity Hallux valgus Plano valgus foot deformity (flat foot) Talipes equinovarus (club foot) Vertical talus
Miscellaneous conditions	Toe-walking Limb-length inequality Arthrogryposis Skeletal dysplasia Developmental dysplasia of the hip (subluxed or dislocated) Osteogenesis imperfecta Congenital limb deficiency/proximal femoral focal deficiency Scoliosis (idiopathic, neuromuscular & congenital)

Table 2: Overview of gait parameters and applications

Gait Parameter	Application		
	Clinical	Sports	Recognition
Stride velocity	X	X	X
Step length	X	X	X
Stride length	X	X	X
Cadence	X	X	X
Step Width	X	X	X
Step Angle	X	X	X
Step time	X		
Swing time	X		
Stance time	X		
Traversed distance	X	X	
Gait autonomy	X		
Stop duration	X		
Existence of tremors	X		
Fall	X		
Accumulated altitude	X	X	
Route	X	X	
Gait phases	X	X	X
Body segment orientation	X	X	
Ground Reaction Forces	X	X	
Joint angles	X	X	
Muscle force	X	X	
Momentum	X	X	
Body posture (inclination, symmetry)	X	X	X
Long-term monitoring of gait	X	X	

There are different methods for capturing gait— gait video, clinical examination, kinematics, kinetics, markerless gait capture, Electromyography (EMG), foot pressure data and energy consumption [2][4][23]. The following figures Figure 1–Figure 8 shows the popular sensors and technique to capture gait pattern and gait parameters [23].

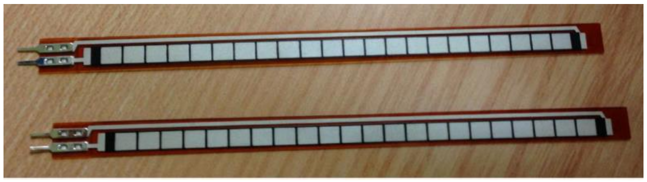

Figure 1: Flexible goniometer [23]

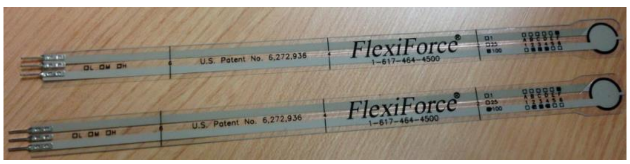

Figure 2: FlexiForce peizoresistive pressure sensor [23]

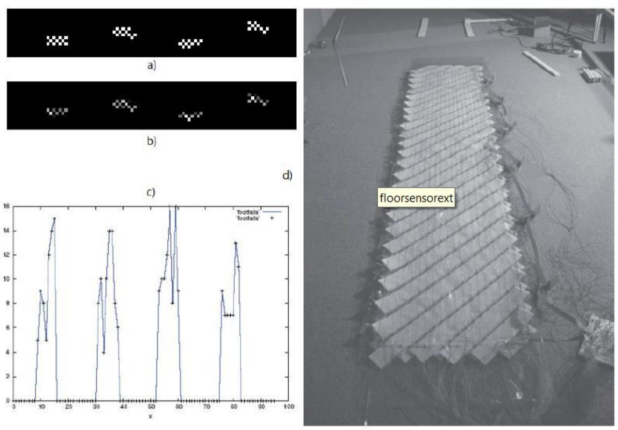

Figure 3: Gait analysis using floor sensors. (a) Steps recognized; (b) time elapsed position; (c) profiles for heel and toe impact; and (d) image of the prototype mat on the floor. [23]

Figure 4: Instrumented shoe from Smartxa Project: (a) inertial measurement unit; (b) flexible goniometer; and (c) pressure sensors which are situated inside the insole [23].

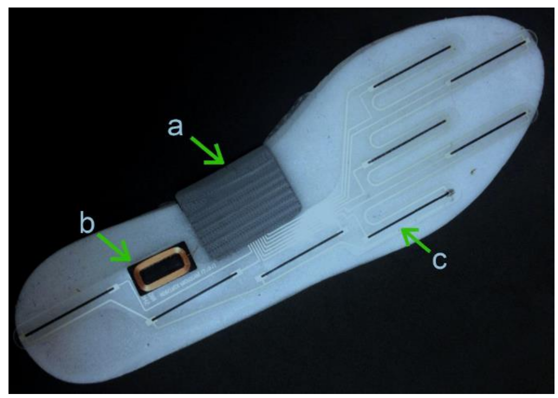

Figure 5: Instrumented insole: (a) inertial sensor, Bluetooth, microcontroller and battery module; (b) coil for inductive recharging; and (c) pressure sensors [23].

Figure 6: Example of NWS system: BTS GaitLab configuration. (1) Infrared video cameras; (2) inertial sensor; (3) GRF measurement walkway; (4) wireless EMG; (5) workstation; (6) video recording system; (7) TV screen; (8) control station [23].

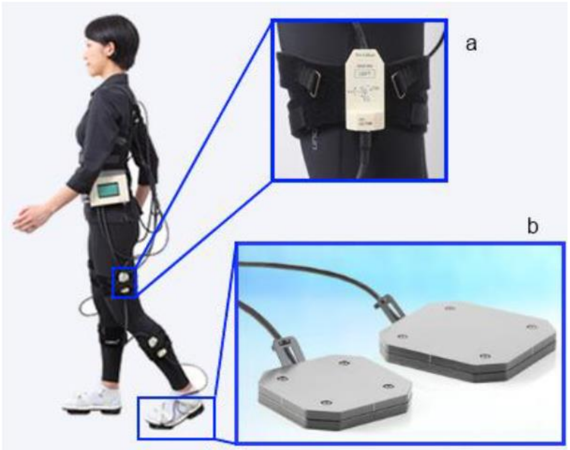

Figure 7: WS system based on (a) inertial sensors; and (b) wearable force plates [23].

Figure 8: Brainquiry Wireless EMG/EEG/ECG system [23].

"Advancement in miniature sensing technology has seen body-mounted inertial sensors being widely considered as a reliable and mobile alternative for gait monitoring. Of late, gyroscopes gained greater popularity in gait event detection [7]." They had a mean error below 7% and the inter-joint angle error of less than 1.1 or 1 degree [1]. Analyzing gait data using professional camera dedicated for gait detection is expensive and limited to laboratory setup [9]. IMUs having the combination of gyro and accelerometer had become an alternative to optical systems and they were low-cost, safe, low powered, and gave continuous, online and offline unobstructed assessment of gait analysis, replacing piezoelectric crystal based accelerometers, which are considered to be large and clumsy [8] [9] [11] [13] and without needing a special treadmill or foot pressure sensing floor or mat [23] [29]. The usual positions of the sensor on human body were—shank, thigh, pelvis, foot and trunk of one or both legs [1] and among these shank was the preferred position to fix the sensor. It was recommended that any sensor that was to be attached to the body "should be small, light-weight, energy efficient and no wires should be needed in order to be worn comfortably and be cosmetically accepted [1] [26]."

We saw that although researchers had done immense work on gait analysis, especially checking reliability on the IMU sensors [1] [3–14] [17] [18] [23] and gait pattern changes caused due to different footwear [15] [16] [20] [21] [22] [24] [27], visualization of the gait data on different foot wear was rarely done [29]. Smart phones, which has an inbuilt IMU sensor, have potential in this area [13][28], but wearing a smartphone could cause to miss/extra gait events and it was preferred to have one IMU on each leg to reduce missed/extra gait events and temporal parameters in case the gait analysis was to be done on hemiparetic subjects [3]. Studies shows that capturing gait parameters by attaching IMU sensors on shank were accurate in the initial contact timing detection, which reduced the errors in stride time and step time than attaching sensor on the waist [6]. So we assert that using two IMU sensor would be enough for building a low cost solution for capturing gait data.

We can capture gait and gait patterns from different footwear using low-cost IMU sensors. Visualizing gait data can also will inform the user that different footwear affects gait pattern. This can possibly inform the user about the reasons for having pain or injury due to her footwear. The visualization might also help the user in choosing better footwear.

PROTOTYPING

Our prototype had the hardware and software part. The hardware part consists of two modules—foot sensor module and shank sensor module, for each foot of an individual. The foot sensor has eight piezoelectric sensors glued to a 0.5mm thickness styrene sheet. The styrene sheet was cutout from an actual shape of both —left and right—foot of an individual of size 10cm. The eight piezoelectric sensors are glued on each cutout such a way that the sensors covered the area touched by the foot on the ground. One layer of 3mm sponge, for left and right foot, was glued on top of the sensor and the styrene cutout and was cut in the same shape. Wires from the piezoelectric sensors were extended to come out of the foot cutout, which would be connected to the extended wires from the shank sensor module.

Figure 9: Cutout of the styrene sheet for left and right foot. The shiny circular coin was the piezoelectric sensor, placed on one of the circular markings of the pressure points of the foot.

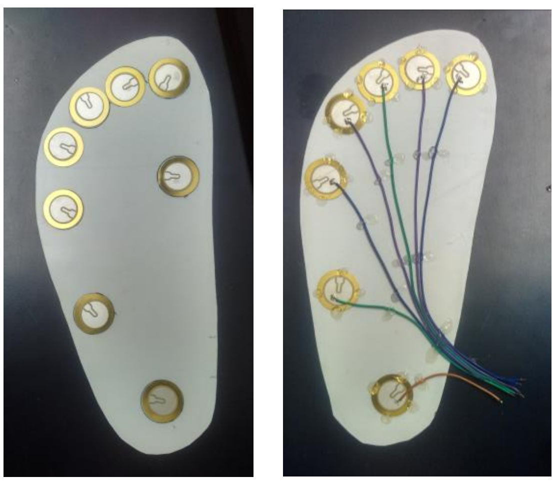

Figure 10: Image shows the foot sensor module for left foot. The piezoelectric sensors were glued to all circular markings and then soldered the wires.

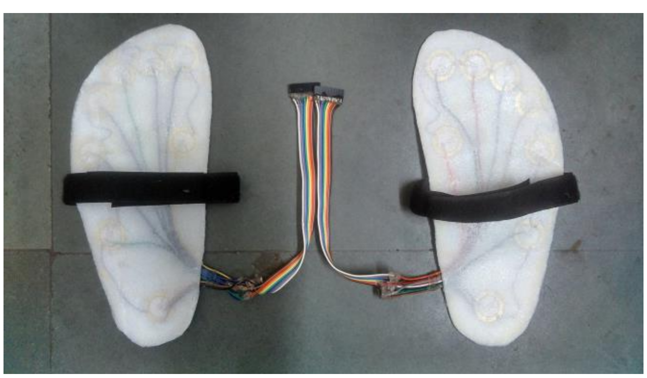

Figure 11: Image shows the finished prototype of the foot sensor module. Black was the Velcro and the white sheet was the sponge layer glued on top of the styrene sheet and piezoelectric sensors.

The shank sensor module consists of the power and motion sensor module. The power module had 360mAh LiPo battery, charger and booster circuit board. The motion sensor module consists of MPU6050 accelerometer and gyro sensor, Arduino Nano, and HC05 Bluetooth module. The shank sensor module had extended wires to connect to foot sensor module, to read the values of piezoelectric sensors.

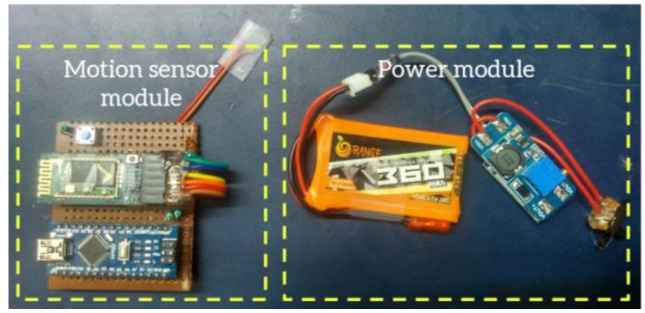

Figure 12: The motion sensor module and the power module.

For software part, other than for coding the sensor to capture values and sending the data to the laptop/pc, we used Python script for saving the gait data—time; yaw, pitch and roll angles, acceleration on x, y and z axis of the IMU, and digital reading of the eight piezo crystal sensors of both legs —in a csv file. Figure 19 and 20 shows the raw readings of the left shank without time. Python script wrote the readings in the csv files for every 40ms. The saved csv file was later opened in Tableau to plot the gait data. In Tableau, we plotted dual axis area chart of pitch vs time graph of both shanks and acceleration on x axis vs time of both shanks. The reason for choosing pitch angle and acceleration on x axis was that the values were better than rest of the axis.

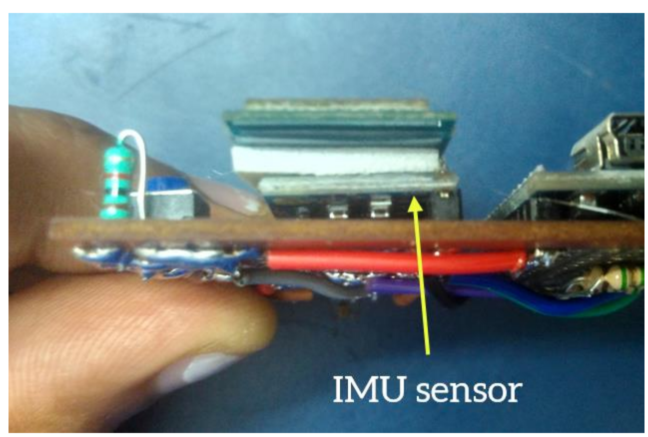

Figure 13: The IMU sensor, MPU6050, was kept under the Bluetooth module to reduce the size of the motion sensor module.

To use the prototype, first the foot sensor module was attached to each legs by Velcro. The shank sensor module—in OFF state—was then attached to each shank by Velcro. Now the extended wires from the foot and shank sensor module were connected together as shown in figure 16. Sensors on both legs were turned ON and the Python script was executed, which automatically connects both the sensors through Bluetooth and then creates a csv file. After the csv file was created, the script starts writing the gait data continuously in the csv file till the script was stopped. The csv file would be automatically saved after the script stopped. The saved csv file was later opened in Tableau to visualize the gait data.

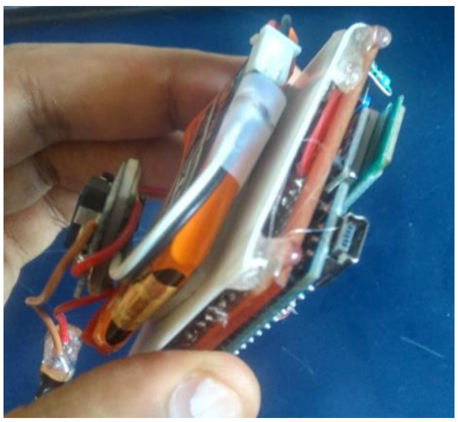

Figure 14: Combined height of shank sensor and power module. The LiPo battery was glued underneath the motion sensor module, separated by a layer of 0.5mm styrene for protection and prevent possible short circuit or thermal damage.

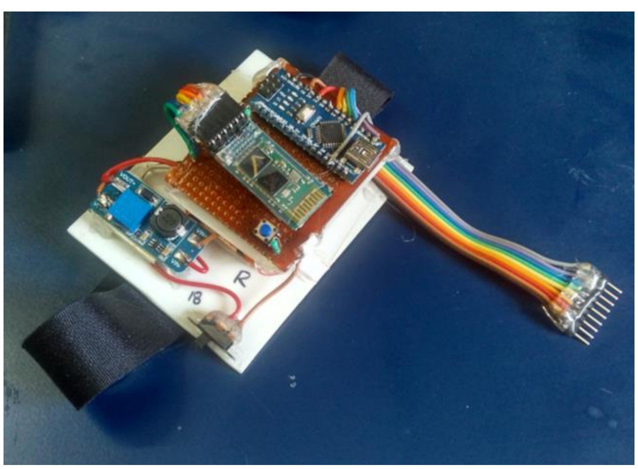

Figure 15: Finished prototype of the shank sensor

Figure 16: Image shows connecting the wires.

Figure 17: Overall size and look after attaching to both legs.

GAIT DATA VISUALIZATION

The dual axis on acceleration of left and right shank vs time was plotted above the dual axis of angular position of left and right shank vs time as shown in the figure 18. We considered using dual axis to visualize the actions happening on both legs simultaneously so that plotting the acceleration and angular position against time will convey unique patterns. The reason for plotting acceleration above angular position of the shank was there are more chances the acceleration will be varied more than angular position of the legs when different footwear was used to walk.

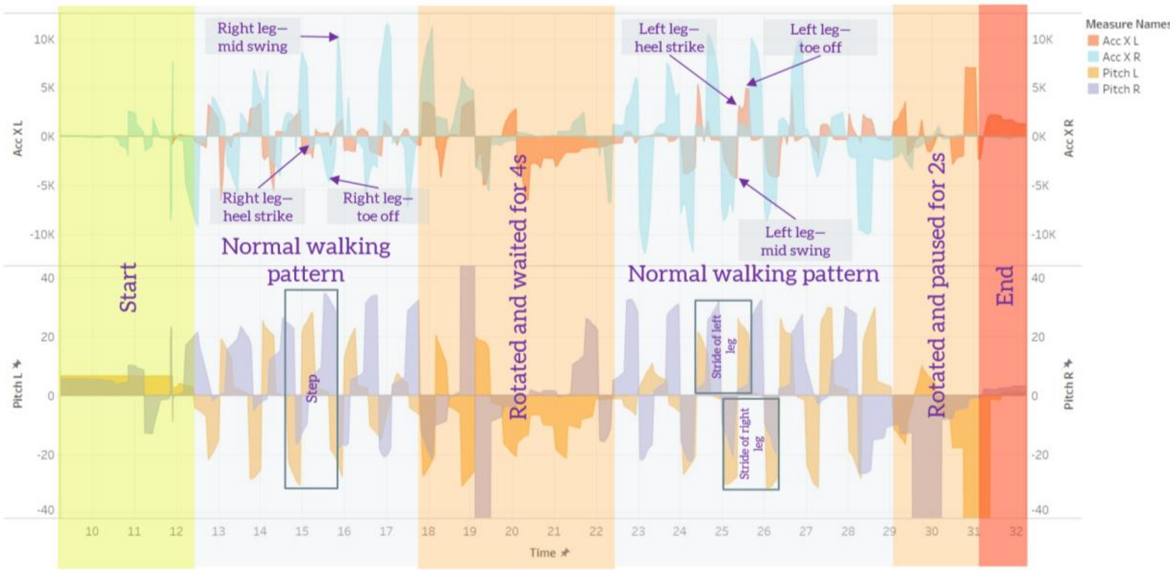

Figure 18: Visualization of gait data captured and gait events from the participant—male 1

In the plots, we chose warm colors for indicating left leg and cool colors for right leg. This color palette was inspired from the navigation lights for aircraft and vessel, where they use red indicator light on left side (port side) and green indicator light for right side (starboard side). Area chart was visually appealing than a line chart and it was easy to identify each leg through colors.

ADVANTAGES OF THE PROTOTYPE

The foot sensor module helped us to detect the toe off and heel strike event of both legs. This also showed the touch points of each legs and reliability of the piezo crystal sensors of the foot sensor module. Figure 19 shows the toe off reading of left leg and figure 20 shows the heel strike reading of left leg. These values would be the mirrored values for right leg.

```
145.12,-10.62,69.76,-318,-379,644,0,0,0,1,0,1,0,0
145.23,-10.74,69.89,-343,-425,705,0,0,0,0,0,1,0,0
145.40,-10.87,70.02,-369,-508,717,0,0,0,0,0,1,0,0
145.72,-11.04,70.17,-376,-538,725,0,0,0,0,0,0,0,0
146.15,-11.27,70.31,-396,-481,794,0,0,0,0,0,0,0,0
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Figure 19: Toe off reading of left leg.

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130.85,3.82,61.87,3745,2762,3047,0,0,0,0,0,0,0,0
129.64,5.80,61.81,3896,2918,3071,0,0,1,1,0,0,0,0
141.96,3.50,64.19,1477,2412,1505,0,0,0,0,0,0,0,0
143.27,2.66,64.20,1368,2289,1505,1,0,0,0,0,0,0,0
144.29,1.93,64.11,618,1778,1191,1,0,0,0,0,0,0
144.95,1.23,63.88,348,1680,1097,1,0,0,0,0,0,0
145.59,0.39,63.70,399,1940,934,0,0,0,0,0,0,0,0
```

Figure 20: Heel strike reading of left leg.

DISADVANTAGES OF THE PROTOTYPE

The foot sensor need to be made universally or made for men and women separately as the foot volume, length and width were not same, and across individuals. The piezo crystal sensors were not flexible to take the shape of the bottom foot, and it gave reading only for the lift and strike of the foot on the ground, not for pressure distribution of the foot on footwear. Therefore the foot sensor modules were not used during user testing. A good reason for not using foot sensor modules for user testing was it could cause new experience for the users. So we gathered the natural walking gait data of the user on barefoot and footwear.

Currently, there was no algorithm/AI/machine learning to identify gait parameters. Therefore understanding and comparison of the gait data visualization on footwear relies completely on the plots.

USER EVALUATION

Nine healthy participants—4 males and 5 females—were chosen, of which one of the male participant was diagnosed for club foot. All the participants were of age group 22–28 years. The time allotted for testing was 45 minutes per participant, which includes attachment of sensors on their legs, linking the sensors with laptop, and saving csv files, each for barefoot, footwear1 and footwear2 gait data. We approached each participants and described her about our research. A nearby tiled veranda to the participant was chosen for testing. Two markers—of colors orange and yellow—were placed on the floor at a distance of 5m between them. We used Xiaomi Redmi 2 smart phone for video recording the test of each participant for future reference.

Each participant was told to select their most comfortable footwear and discomfort footwear, and asked to come barefoot to the veranda. Sensors were then attached to the outer side of her shanks. Laptop and sensors were setup and linked wirelessly. Sensors were calibrated and tested for reliability before the test commenced. We took permission from each participant for recording their test. The smartphone was mounted on a phone tripod and placed near to the yellow marker, such that it captures only the leg and records the front and back of her walk.

When the test started, the smartphone camera was recording, the Python script was run and the participant was instructed to walk straight in her normal way from yellow marker to orange marker, rotate and face towards the yellow marker for two–four seconds. The participant was then asked to come back from orange marker to yellow marker and again instructed to rotate and face towards orange marker for two seconds. The csv file for her barefoot gait data was saved in the laptop and was opened in Microsoft Office Excel to check for any blank data. If no problem was found in the file, then the participant was directed to wear her footwear1 and asked to repeat the same tasks given for barefoot, otherwise she was asked to do the task once again. Python script for footwear1 was run. The process continued till footwear2, after which the test concluded. After the test, the sensors were disconnected from the laptop and detached them from her foot.

The analysis on the gait data of the participants began after the testing of all the nine participants got over. When the analysis got over, each participant was shown the visualization of her gait data as well as gait data of others from the laptop. We described them about what were the each data shown in the plots i.e. figure x–x. User was directed to evaluate the visualization of the gait data based on the given questions:

a. Understanding of the data visualization.
b. Relation of the colors to what they were meant for.
c. What does the comparison tells about.
d. Usefulness of the visual and the information
e. Applications and the reason for it.
f. Did it inform the user to wear good footwear?
g. Problems in wearing the sensors—irritation, weight, safety.
h. Were the sensor attachments convenient and quick to setup for use.
i. Was there a need to have any manual/reference and reason for the same.
j. List out the pros, cons, suggestions, recommendations, area of improvements and removal on the system.

RESULTS AND ANALYSIS

The normal barefoot walking gait pattern of all the participants were different, but there were signs of how an average normal barefoot gait pattern would look like—mirrored ‘L’ shape and inverted ‘L’ shape for each leg. We observed the stance time—which includes heel strike point and toe off point—was more than the swing time. Figure 21 shows the visualization of the walking gait data of the participant—male 1, in his customized shoe. A link to comparative gait visualizations of males and females in barefoot and footwear is provided under the sub heading—External link. When participants wore their footwear, the acceleration and the angle as well as the swing and stance time of both legs got altered. Men and women who wore expensive and comfortable shoes were able to achieve their barefoot walking gait. When they wore heeled footwear—formal shoes, boots, heeled slippers and heeled pumps—there were spikes in the acceleration vs time graph. Women who wore less or no heeled pumps, the spikes were less. Comparing between male and female participants, they had similar barefoot walking gait patterns. Male—3 and female—3 had similar walking gait patterns as their both legs made positive angle deflections in their stance time and negative angle deflections in their swing time. The male participant, who had a customized footwear that he wore to correct his deviated gait pattern to normal, as he was diagnosed for club foot. The result after he wore the customized footwear made his walking gait symmetrical, as in figure 18—male 1, and said that footwear was the most comfortable footwear he had used till now. These

Male 1

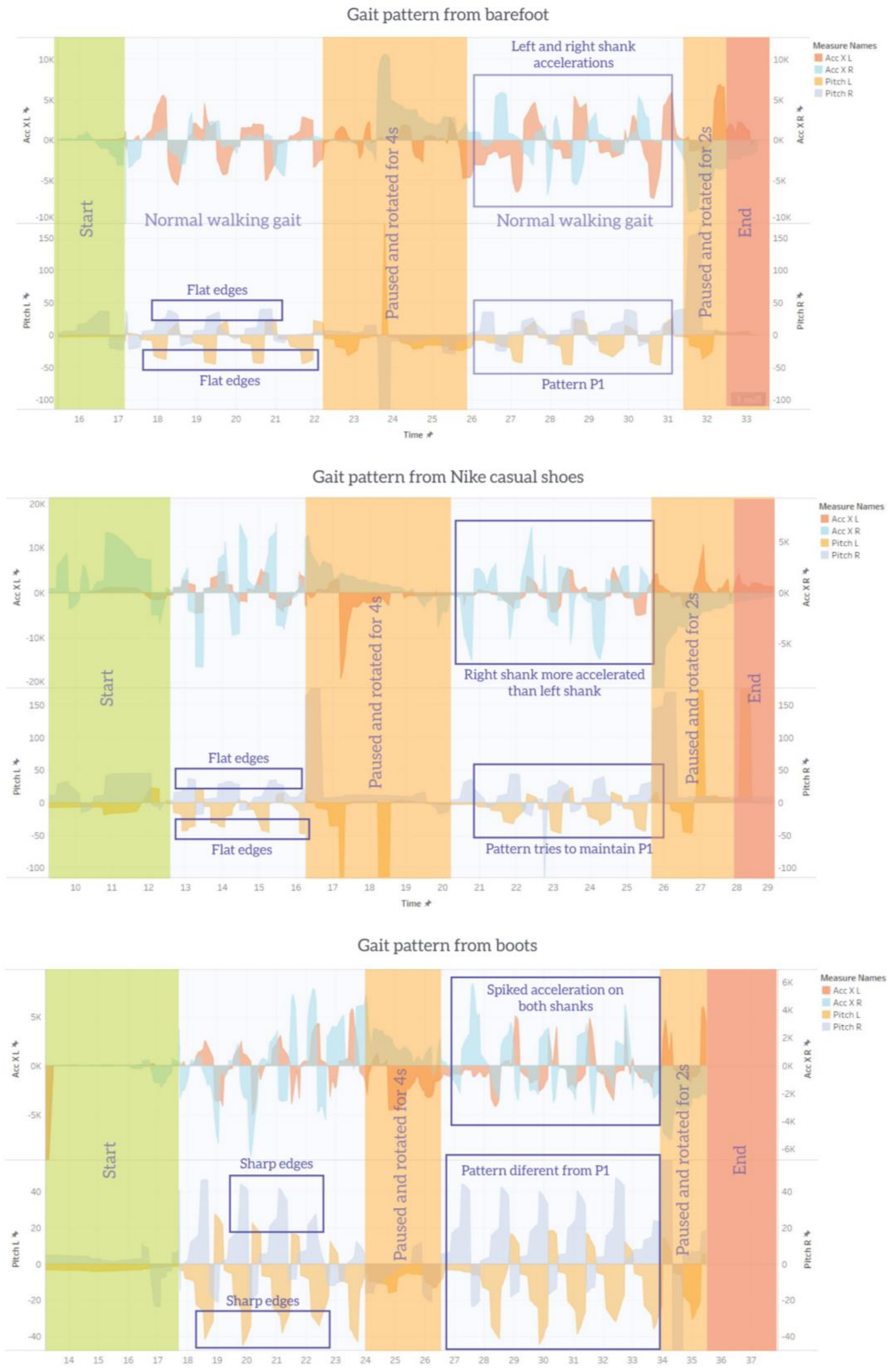

Figure 21: Analysis on visualization of gait data captured from the participant—male 2

information concluded that a customized and comfortable footwear will maintain the normal gait pattern

Participants for the first time saw the difference in their left and right gait pattern. They agreed that the gait pattern changed when they wore footwear and was different from others. The plots were very useful and also informed the participants about how their foot coordinate when they walked, informed them to wear comfortable footwear and this will be a preferred choice along with aesthetics of the footwear when they buy it for the next time. Colors used in the plots could not inform the users which color for which leg. Participants suggested that the visuals of changes in the angle and pressure points of the foot will be inform people better than plots, if done without assistant. One of the participant gave a tip that using metronome beats can guide the participants to walk with rhythmic steps, which can reduce the error caused due to uneven number of steps made by the participants in the given distance.

Participants responded that the visualization of the gait can be applied as a live gait plot or their suggested visual representation of the foot with comparison in footwear shops so that people can watch the changes happening when they choose different footwear and it will be very useful for people looking for comfort and sports. Gait visualizations can applied for rehabilitation centers to inform doctors and their patients about the treatment progress, areas of physiotherapy, for patients who are going to wear prosthetics or customized shoes to establish normal gait pattern, area of sports—those players who need to improve their running performance, and may be creating a new standardization for footwear based on comfort rating. One of the female participant proposed a novel application using this gait visualization in offices, where office workers may sit and work continuously for hours without taking a break to move around, which lead to posture problems. This can affect their gait patterns directly. Therefore visualizing gait patterns by office workers—weekly or monthly—can suggest their possible causes of pain or posture problem.

Participants pointed out that there were possibilities the shank sensor could slip. The reason could be the flat base of the shank sensor, which would not go ergonomically to the shank and the use of Velcro instead of elastic band. So they suggested to use side strap release buckle with ladder lock slider buckle mechanism that comes with a backpack, so that the shank sensor will be kept rigid with the shank.

External link
https://github.com/enlinquental/DRS_gait_plot_participants

DISCUSSION

The gait plots were directly affected by the shank sensor position and disturbances caused on it while walking. Possible reasons for skewed or irregular plots could be usage of Velcro strap, which instead should have been used a strap buckle that participants had pointed or the shank sensors could have used a sticky surface with shock absorption to stick directly on the participants' shank. We did not use any measuring tape to measure the shank sensor's vertical and angular position on the participants' leg from a reference point, which was reflected in the plots.

We should have taken three–four readings of each walking gait patterns of the participants on barefoot and footwear, and average them to improve the gait plots, which will remove minor errors. Another way to improve gait plot can be increasing the to and fro distance or a 10m–20m one way straight path, which can remove the initial experience of wearing with and without footwear, which is reflected in first walking phase of the participants'. We are considering suggestion made by one of the participant—for our future tests—to use metronome beats, which can guide the participant to take rhythmic steps during her walk, which causes participants to make even number of steps.

CONCLUSION

We developed a low cost IMU sensor based device to capture and visualize the changes occurring in gait patterns when different type of footwear was worn. Participants positively agreed that wearing their footwear changed their gait patterns from their barefoot gait pattern. They responded that the information shown from gait patterns from their footwear as well as from others was informative and will be considering to wear comfortable footwear so as to maintain their normal barefoot walking gait pattern. Future work includes implementing algorithms or machine learning to the device for auto detection of gait parameters, visualization of foot and its related comparison as suggested by the participants, so that people can understand without assist. In future, IMUs, especially the accelerometer based sensors, have a "promising ambulatory monitoring technique that could be used for the assessment of mobility in routine clinical practice [9]."

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