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Laboratory In A Box: Wearable Sensors And Its Advantages For Gait Analysis

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Abstract—**Until recently, many gait studies explored potential gait alteration due to various disorders in the gait lab and using camera based systems and force platforms. However, these strategies may not replicate normal outdoor walking. Using this equipment, it is more difficult to measure the variability of walking which is important for maintaining balance and responding to different walking challenges. Additionally, subjects may mask their problem or exaggerate it when they are walking in a short walking distance offered by laboratory based-technology. This study overviews some of the key advantages of wearable technology compared to laboratory-based instrument. Additionally, it explored gait patterns over ample distance of walking compared to walking distance restricted to a gait laboratory environment. Walking patterns of ten healthy young subjects were examined using a wearable sensor technology in a random order over a distance of 7m, 14m, and 20m. Results suggest that participants walk significantly faster by increasing walking distance on average by 15% and 3% when walking distance was increased respectively from 7m to 14 and from 14m to 20m ($p<0.05$). Interestingly despite a high test-retest reliability for averaged gait parameters (ICC>0.89), the test-retest reliability for gait variability was only acceptable during 20m walking distance (ICC<0.3 for 7m and 14m v. ICC=0.65 for 20m). Taken together, our findings indicate that for valid and reliable assessment of gait parameters, gait should be performed over ample walking distances. Body worn sensor technology facilitates assessing gait outside of a gait laboratory, over ample walking distance, different footwear condition, different walking surface, and in environment where mimics better true environment where the subject is active in.**

I. Introduction

PROPER gait function (i.e., quality of walking) requires the ability to maintain safe gait with optimum energy cost while navigating in complex and challenging environments. [1] Gait disorders and diminished ability to walk safely are associated with an increased risk of falling, increasing energy cost and consequently causing musculoskeletal pain[2], which may lead to reducing mobility and quality of life.

Until recently, assessing and quantification of gait function outside of the constraints and subsequent methodological issues of the gait lab have been elusive. Traditionally, gait is assessed using laboratory-based instruments such as optical motion measurement systems and force platform in a gait laboratory.[3-5]. Although these systems are clinically accepted as 'the gold standard', there have been several drawbacks. Firstly, the number of consecutive strides that can be measured is limited. This means that inter-cycle variability of gait, involved in balancing the body and walking during varying circumstances, cannot be investigated using the existing systems as it requires a larger number of consecutive strides to be measured.[2, 6] Instrumented treadmills can address this limitation; however, uncertainty remains regarding the extent to which treadmill walking can be used to mimic overground walking[7]. In addition, the narrow path offered by the treadmill as well as small freedom for inter-cycle speed variability may hinder freedom in selection of gait trajectory or speed. Therefore, it may not replicate natural gait behavior of subject during everyday life. Finally, recent studies revealed that subjects may modify their gait pattern when walking outside of a gait laboratory environment. [5] These results may indicate that gait parameters assessed inside of a gait laboratory environment may not replicate subject's gait outdoors in which subjects may walk a longer walking distances on different walking surfaces and irregular pathways.

Recently, an alternative technology based on electronic walkway (e.g. GaitRite®) was introduced allowing assessing gait outside of a gaitlab and over several steps of walking. However, they are still suffered from several shortcomings that may mask subject's gait deterioration. For example, such technologies have limitation of exploring the impact of type of surface on gait alteration[8] or examining gait on different pathway and ample walking distances.

Advances in the technology of body-worn sensors during the last decade have allowed investigators to use this technology for measuring various aspects of human performance. These areas include studying the spatio-temporal parameters of gait [4, 5, 9, 10], joint and segment angles (kinematics) [11-14], monitoring spontaneous daily physical activity [15-22], and evaluating the fear of

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falling[23], and risk of falling. [24] These studies are based on the use of miniaturized and integrated sensors in combination with lightweight, small measuring devices that can be carried without interfering with normal activity.[4] One of the main advantages of body-worn sensors compared to laboratory-based measuring systems is that they are ambulatory and can be used in free conditions continuously over long periods of time. [5] This study overviews the importance of gait analysis over ample walking distances, one of the key conditions that can be easily explored using wearable sensors.

II. Wearable sensor –advantages and challenges

A. *Wearable sensors- advantages and challenges*

Rapid advances in wireless communications and networking technologies, linked with advances in miniaturization of electronic circuits and optimization in power consumption, facilitate the development and offering of emerging wearable sensors and devices in the healthcare sector. Unlike laboratory-based instruments, which need a dedicated controlled space, the wearable sensors can be used just about anywhere. [4] It is highly transportable and does not need any stationary units such as transmitter, receiver or cameras. In addition, these sensors are much cheaper than sonic, magnetic and optical motion captures.[4] They are easy to set up and use, and do not require highly skilled operators. The wearable sensors can be used in real time, since the processing phase of detected signal is much shorter than the computing time of some standard systems using image processing and marker tracking algorithms.[4] In particular, combination of multiple accelerometers, angular rate sensors (gyroscopes), and magnetometer show a promising design for a hybrid kinematic sensor module for measuring the 3D kinematics of different body segments. [13] These sensors incorporated with a high speed data acquisition system enable the measuring and recording 3D body segment motion with sample frequency much higher than camera based system. The high sample frequency is of key importance to create an altered dynamic environment to evaluate the postural response against alteration. In addition, a real-time processing is very beneficial for creation a bio-feedback signal from body segment motion for both rehabilitation and evaluating of the motor adaptation/control mechanisms.

A key challenge, however for using wearable sensors is their ability to extract useful clinical data along with restriction on number of sensor attachment and ease of management. Naturally, if the wearable sensor poses any hindrance to the subject's movements, due to either the complexity of sensor attachments (e.g., multiple sensor units, location of sensor attachment, etc), or device management (e.g., limited battery life), its clinical application and it particular for outdoor monitoring and routine clinical assessment will be limited. Therefore, simplified biomechanical model of human body combined with advanced signal processing should be integrated with such technology to translate them for various clinical applications. On the other hand, unlike to laboratory based motion analyzer systems, which can be used for a wide range of motion analysis applications, the technology based on wearable sensors are designed for specific applications depends on desired duration of recording as well as restriction on number of sensors, cost, and usage environment. For example, for assessing risk or fear of falling during activity of daily living[23, 24], where a subject should carry the sensor continuously during his/her daily life and over several days, the system should be highly comfortable, should have enough long battery life, and should be able to be worn unobtrusively. These criteria will limit the number, type, and place of sensor attachment. This in turn required adaptation of simplified version of biomechanical model of human body for extracting clinical meaningful information depends on type, number, and location of attached sensors.

III. LegSys™: A Wearable technology for extracting spatio-temporal parameters of gait

Recently Aminian, Najafi and colleagues[9] introduced a novel algorithm and a two-link inverse pendulum model allows extracting accurately spatio-temporal parameters of gait. A device based on this concept has also been commercialized and named LegSys™ (Biosensics, MA, USA). The device uses five sensor modules respectively attached to right and left anterior shins, right and left anterior thighs, and posteriorly to the lower back (Fig1). Each sensor measures the angular velocity of the segment around the medio-lateral axis (flexion-extension). The method for calculating spatio-temporal parameters of gait has been described in detail in previous publications [9, 15, 25]. To summarize, the gait phases are determined from the precise moments of heel-strike (initial foot contact) and toe-off (terminal foot contact). These moments are extracted from gyroscopes attached to each shank through a local minimal peak detection scheme [9, 15]. Based on the subject's height and using a two-link inverse pendulum model, spatial parameters (e.g. lower limb stride length and stride velocity), can be estimated by integrating the angular rate of rotation of the thigh and shank [9, 15]. Finally, to assess center of mass displacement during walking (e.g., medio-lateral & anterior-posterior rotation of center of mass per cycle), another sensor is attached to lower-back including a tri-axial gyroscopes and a tri-axial accelerometer. This sensor module provides range of motion estimates for center of mass for each cycle in medial-lateral and anterior-posterior, and therefore allows us to assess a subject's postural control during gait. The algorithm has been validated in patients with hip osteoarthritis, with total hip replacement, elderly, and control subjects [4]. A force-plate and an optical motion analysis system including four cameras have been used as a criterion standard in these validation studies. The correlation with camera results was more than 0.97 and the root mean square (RMS) error was less than 4 degrees for estimation of segment angles. On the

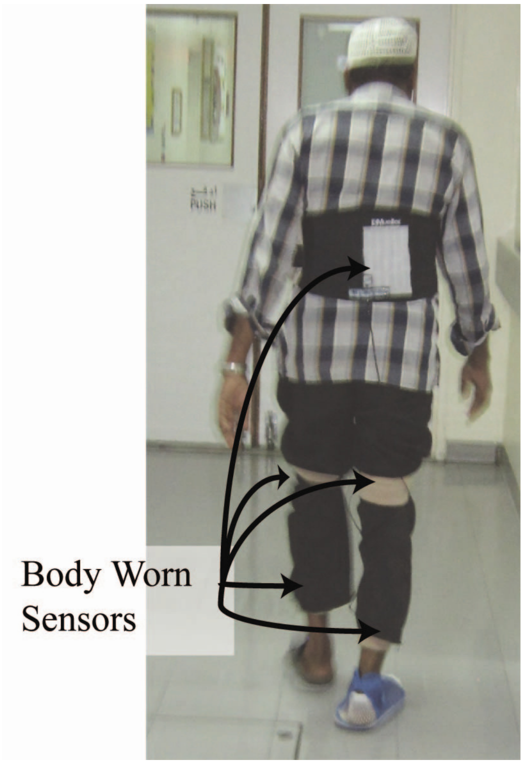

Fig 1. LegSys™. A wearable sensor technology for extracting spatio-temporal parameters of gait outside of a gait laboratory, over different footwear condition, walking surfaces, and in the environment where may better mimic true patient's living environment.

same note, RMS error for estimation of stride velocity and stride length was respectively less than 0.07m/s and 0.08m.[5] In another study, a relatively test-retest reliability (ICC>0.82) for estimation of stride velocity and gait cycle was reported including a group of 27 older adults walking with different gait speed ranging from 0.6m/s to 1.4m/s.[5]

IV. Gait Analysis and its Dependency on Walking Distance

In a recent study[5] including 27 older adults (age: 80.3±5.0 year), we examined whether the gait assessed inside of a gaitlab and over limited walking distance can replicate the gait measured outside of a gaitlab and over longer walking distance. Interestingly, we observed that elderly participants walked 5.2% ($p<0.05$) faster over long walking distance compared to short walking distance despite a high test-retest reliability (ICC>0.82) for both conditions. Moreover, the test-retest reliability of gait automaticity assessed using coefficient of variation (CV) of stride velocity was improved over longer walking distance (ICC=0.50 for long v. 0.37 for short walking distance). This study was however unable to examine whether the observed gait increase was due to performing gait study outside of gaitlab or is due to increasing walking distance. To address this question we designed the present study. We examined the gait patterns of ten healthy young volunteers (eight men and two women, age: 25.8±2.2; BMI: 24.4±4.6) on three walking distances (7m, 14m and 20m) in a randomized order and in an identical environment condition. The study received the ethical approval from the Institutional Review Board (IRB) at Rosalind Franklin University. All participants received oral and written information and signed informed consent before participating. For all conditions gait parameters were extracted using wearable sensors (LegSys™, Biosensics LLC, MA) in a hallway outside of a gaitlab. The walking environment was identical between three trials and all subjects were asked to walk with their habitual speed while wearing their regular shoes. Each testing condition was repeated on the same session to examine test-retest reliability. Although LegSys™ provides a wide range of spatio-temporal parameters of gait, in this study we focused on (1) the mean stride velocity (SV), 2) the mean gait cycle time (GCT), (3) the mean of stride length (STL), (4) the mean of stance time (ST), and (5) the inter-stride variability of stride velocities expressed by its coefficient of variation (CV(SV)). Statistical analyses were performed using SPSS® version 15. A paired sample t-test was used for comparing between different walking distance conditions. ANOVA and a *Post Hoc* test of Scheffe was used to examine whether the gait velocity is changed as a function of walking distance. The relative test-retest reliability was evaluated using intraclass correlation coefficient (ICC(1,1)).

Results suggest that the stride velocity (SV) increased significantly by increasing walking distance ($p<0.05$). Specifically, by increasing walking distance from 7m to 14m, SV was increased on average by 15% (0.16m/s, 95%CI=[7,24]%, $p<0.001$). On the same note, STL was increased by 7% while gait cycle time (GCT) decreased by 6.7% when increasing the walkway distance from 7m to 14m. When comparing 7m and 20m, we noticed that SV increased significantly (0.21m/s (20%), 95%CI=[0.11,0.29]m/s, $p<10^{-5}$). Similarly when we compared 14m and 20m there was still a moderate increase by 3% (0.04m/s, 95%CI=[0.004,0.08]m/s, $p<0.05$) in SV. Table I summarizes the comparison results between different walking conditions.

TABLE I
GAIT MODIFICATION AS A FUNCTION OF WALKING DISTANCE

Gait parameter	14m-7m		20m-7m		20m-14m	
	Inc/Dec	P-value	Inc/Dec	P-value	Inc/Dec	P-value
SV	0.16m/s (15%)	$<10^{-3}$	0.21m/s (20%)	$<10^{-5}$	0.04m/s (3.3%)	0.03
GCT	-0.08s (6.7%)	0.003	-0.08s (9.8%)	$<10^{-5}$	-0.03s (2.6%)	0.01
STL	0.09m (7%)	0.01	0.10m (8%)	0.002	0.01m (0.7%)	0.41
Stance	-0.31% (0.5%)	0.62	-1% (1.6%)	0.19	-0.69% (1.1%)	0.04

Inc/Dec: Increase or decrease presented in absolute and relative values.

Interestingly, despite a high test-retest reliability for the averaged values (ICC>0.89), only during 20m gait test, the test-retest reliability of CV values were acceptable (ICC<0.30 for 7m and 14m v. ICC=0.65 for 20m).

V. CONCLUSION

Research done by our group suggests both young and older adults walk differently (e.g., faster) outside of the gait lab when they don't be distracted by the equipment. Limited number of strides captured by laboratory-based instruments may influence the stability of the mean and variation estimates. Similarly, the high gait variability associated with gait disorders would require a higher number of strides to provide a more stable estimation of mean values. Advance in wearable technology combined with simplified biomechanical model of human body now offer the possibility to explore gait outside of the gait laboratory, over ample walking distance[5], different footwear conditions[2, 6], different walking surface[8], and where the distraction by the environment is minimal or better replicate the true environment of the patient.

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