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Electronically augmented gait abnormality assessment following lower extremity trauma

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Abstract

Background: Objective evaluation of patient outcomes has become an essential component of patient management. Along with patient-reported outcomes, performance-based measures (PBMs) such as gait analysis are an important part of this evaluation. The purpose of this study was to evaluate the validity of utilizing a wearable inertial measurement unit (IMU) in an outpatient clinic setting to assess its ability to provide clinically relevant data in patients with altered gait resulting from lower extremity trauma.

Methods: Five orthopaedic trauma patients with varying degrees of gait pathologies were compared to 5 healthy control subjects. Kinematic data were simultaneously recorded by the IMU and a gold standard Vicon video motion analysis system (Vicon Motion Systems Ltd, Oxford, UK) during a modified 10-m walk test. Raw data captured by the IMU were directly compared to Vicon data. Additionally, 5 objective gait parameters were compared for controls and the 5 trauma patients.

Results: The IMU data streams strongly correlated with Vicon data for measured variables used in the subsequent gait analysis: vertical acceleration, vertical displacement, pitch angular velocity, and roll angular velocity (Pearson r-value > 0.9 for all correlations). Quantitative kinematic data in post-trauma patients significantly differed from control data and correlated with observed gait pathology.

Conclusions: When compared to the gold standard motion capture reference system (Vicon), an IMU can reliably and accurately measure clinically relevant gait parameters and differentiate between normal and pathologic gait patterns. This technology is easily integrated into clinical settings, requires minimal time, and represents a performance-based method for quantifiably assessing gait outcomes.

Level of Evidence: *Diagnostic Level 1.*

Abbreviations: 3D = 3-dimensional; BMI = body mass index; DS2DS = dual-stance to dual-stance; IMU = inertial measurement unit; P2P = peak to peak; PBM = performance-based measures.

Keywords: gait assessment, inertial measurement unit, lower extremity trauma

1. Introduction

Objective functional assessment of patient outcomes continues to become more important to patients, clinicians, and payers in our current health care environment. A valid, reliable, objective measurement of outcome is important both for monitoring the clinical progress of individual patients and also as a research tool to evaluate outcomes for different interventions. Although patient-reported outcome measures play a crucial role in assessing outcomes, in the absence of additional PBMs they provide only subjective results, which may not reflect functional status.

For a PBM to be useful in both a clinical and research setting, it should be accurate and reproducible, objectively capture clinically meaningful functional information, and involve a quick and convenient measurement and interpretation. Commonly used PBMs in the clinical setting include the timed-up-and-go test and the stand-sit test.[1,2] However, these tests produce results of limited interpretability (only measure the total time to accomplish a task), and cannot capture more subtle alterations in gait and function. In an attempt to better quantify pathologic function, more comprehensive 3-dimensional (3D) motion capture analysis has also been used to analyze gait,[3–6] and these systems have been used specifically in limited series in orthopaedic trauma patients.[7–13] However, these laboratory-based studies require systems that are expensive, time-consuming to set up, difficult to interpret, and are not generally practical for routine clinical use or broad-based research application.

One technological approach to measure physical performance has been through the use of IMU.[14] IMUs are currently commonly utilized in commercial electronics ranging from

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cellular phones to unmanned drones and provide continuously updated orientation data using accelerometers, gyroscopes, and magnetometers. They have also been used to objectively assess gait in healthy patients,[15] as well as patients with fall risk,[16] knee arthritis, and arthroplasty.[6,17–20] These systems are generally simple to apply, require minimal setup time, and return useful kinematic data.

The purpose of this study was to evaluate the validity and feasibility of using a single chest-mounted IMU smaller than the size of most commercial pagers for capturing objective gait data in an outpatient clinical setting, compared to a Vicon motion capture system in a formal gait lab. Furthermore, we aimed to evaluate essential kinematic parameters associated with altered gait resulting from lower extremity trauma compared to healthy individuals. Our hypotheses were that the IMU data capture and analysis system would: produce raw acceleration and angular velocity data that closely correlated to that captured using a video-based motion capture system, and capture data that can quantitatively assess differences between normal and pathologic gait.

2. Materials and methods

2.1. Participants

This study was conducted with approval from our Institutional Review Board, and all participants gave informed consent. Data were gathered on 10 total subjects, which included 5 patients who had previously sustained lower extremity trauma, and 5 age and gender-matched controls. For the orthopaedic trauma patients and control patients, the average ages were 34 and 30 years, respectively, and the average body mass index (BMIs) were 27 and 26, respectively. For the trauma patients, the average time from injury varied from 12 to 82 months (average 39 months). Full demographic characteristics as well as injury information for the orthopaedic trauma patients with corresponding controls' data are displayed in Table 1. Patients had sustained multiple different lower extremity injuries including proximal tibia fractures, open tibial shaft fractures, midfoot fracture dislocations, as well as crush injuries, and displayed a variety of different gait patterns (representative de-identified gait segment videos for patients 1, 3, and 5 are also attached as a supplement to augment later discussion, http://links.lww.com/OTAI/A3; http://links.lww.com/OTAI/A4; http://links.lww.com/OTAI/A5). Subjects were compensated $100 for their time and to help with transportation costs.

2.2. Motion data capture devices

Motion data were captured using a standard 10-camera Vicon video motion capture system. The IMU was outfitted with its own marker triad which allowed the Vicon system to independently measure 3D acceleration and 3D angular velocity data for the torso IMU mounting location for direct comparison. Additionally, the participants were fitted with a full-body marker set so overall kinematic data could also be captured. Setup time for the Vicon system is approximately 20 minutes, and requires that patients travel to a dedicated gait laboratory at a separate facility. The total purchase cost of a Vicon system used in a gait laboratory typically ranges from approximately $100,000 to $250,000 depending on the number and quality of cameras used and the supporting analysis software.

The IMU was a chest-mounted unit (Opal Monitor, APDM Inc., Portland, Oregon) positioned at the top of the sternum using a simple harness (Fig. 1). The Opal is a wireless telemetry, 10 degree-of-freedom unit which includes a tri-axial accelerometer, a tri-axial gyroscope, a tri-axial magnetometer, and an onboard temperature sensor. Custom software was developed to appropriately filter the raw data, establish a fixed global coordinate system (i.e., aligned with the body coordinate system), segregate gait segment data from turn data, and delineate and compile data for left and right strides for separate analyses. The software is also used to calculate quantitative descriptors of gait which are observable during subjective gait evaluation but not readily quantified (described below). Setup and test time for the IMU is approximately 5 minutes and is easily performed in an outpatient clinic setting. The total purchase cost of the apparatus in the IMU system is approximately $2500 including the device, wireless sensor, computer, and software.

2.3. Performance testing protocol

Participants completed a modified 10-m walk test which involved the subject starting from a standing position, walking 5 m at a comfortable pace, turning around, and then walking back 5 m to the original starting point. The test was repeated twice for each subject so that 4, 5-m walk segments were assessed. This sequence allows for the analysis of 10 to 12 full strides (i.e., accelerating and decelerating strides removed) to be analyzed for each limb. This modified gait protocol was selected as to be amenable to most clinical settings with regard to typically available physical space in an orthopaedic clinic and available time to administer the evaluation.

Table 1

Patient orthopaedic injury information and demographic data with corresponding control demographic data.

Fracture patients									Control patients					
Pat #	Gender	Age, years	Ht, in	Wt, lbs	BMI	Injury	OTA class	Time postop, months	Cont #	Gender	Age, years	Ht, in	Wt, lbs	BMI
1	Male	45	70	195	28.0	Tibial plateau fracture ®	41C.3	16	1	Male	48	69	208	30.7
2	Male	24	73	220	29.0	Lisfranc and midfoot fracture/ dislocation (R)	87.1	71	2	Male	22	72	195	26.4
3	Male	29	70	150	21.5	Open distal tibia/fibula fx (R) Foot/patella fx (L)	43C.3 34C	12	3	Male	25	70	175	25.1
4	Female	44	60	153	29.9	Open tibial shaft fracture (L) Posterior malleolar fx (L)	42A 44B	12	4	Female	22	67	135	21.1
5	Male	30	64	148	25.4	Open tibial shaft fx (R) Open tib/foot crush (L)	42A 42A	82	5	Male	32	71	195	27.2
Mean	4M:1F	34.4	67	173	26.8			38.6	Mean	4M:1F	29.8	70	182	26.1

Figure 1. Image of the harness and IMU (APDM Opal Monitor) noting location of sensor package at the top of the sternum.

2.4. Analysis—data fidelity

The Vicon system and the IMU use different methods to capture kinematic data. Vicon continuously collects displacement data from reflective markers and then uses that data to calculate both linear and angular velocity and acceleration data. IMUs collect raw acceleration and angular velocity data and use that data to calculate linear velocities and displacements along with angular displacements and accelerations.

Simultaneous vertical acceleration, vertical displacement, pitch angular velocity and roll angular velocity output waveforms collected directly or derived from both the IMU and Vicon raw data streams were compared across all gait segments during all tests. Individual subject correlations between the IMU and Vicon data were evaluated by Pearson r calculations, using the MATLAB xcorr cross-correlation function. Aggregate correlations were calculated separately for the lower extremity trauma group and the control group to determine if gait pathology resulted in poorer correlations for the Vicon and IMU data streams as compared to normal gait patterns.

2.5. Analysis—gait characterization

There are many variables that can be used to quantify gait characteristics which include inequalities in time spent for left versus right strides, asymmetries in extremity motions, and exaggerations of motions of the upper body which shift the center of mass off of its normal path.[13] These are recognized compensatory mechanisms used for weight or pain avoidance or functional insufficiency with recovering limbs.

The variables that were selected to assess gait pathology were therefore based on these clinical observations and included mean difference in left versus right vertical accelerations indicative of different push-off forces, mean differences in left versus right stance times, mean cyclical vertical displacement of the torso, along with mean cyclical forward/backward pitch, and mean side-to-side roll of the torso during gait. Taking the difference between left and right values for these allows normalization for patient body size and habitus as well as gait velocity.

During the gait cycle there is maximal vertical acceleration between heel strike and toe-off when the center of mass is lowest and begins to displace upwards. Likewise, there is a peak negative vertical acceleration during mid-stance phase when the center of mass is highest and begins its downward descent toward the next heel strike. The time spent in stance phase for each leg can be measured as the difference between vertical acceleration peaks. This period is often shortened on the pathologic side as accommodative strategies are employed to minimize time on the painful/disabled limb. We denote this period as "dual-stance to dual-stance (DS2DS)" time. The difference between minimum acceleration and the maximum acceleration on each limb can then be calculated as a "peak to peak acceleration," which is likewise diminished for the affected limb during single-leg stance indicative of a less forceful vertical push-off.

Similarly, normal gait is associated with cyclic changes in upper body vertical displacement, sagittal plane angulation (also called "pitch") and upper body coronal plane angulation (also called "roll"). The total difference between maximal position and angulation in both planes can be calculated to measure the net displacements during the gait cycle. These displacements typically increase in pathologic gait as the torso increasingly moves to more extreme positions to minimize joint reactive forces or accommodate for stiffness, weakness, or pain in the lower extremity.[21] This separation of selected gait variables into lower extremity and upper body variables mirrors video scoring measurements used in the Gait Abnormality Rating Scale.[22–25]

For each of the 4 gait segments (i.e., 2 segments × 2 tests), 3 maximal pitch (forward) and 3 minimal pitch (backward) values were used to calculate the peak-to-peak pitch value for that segment. The pitch results for 4 gait segments were combined to produce the mean peak-to-peak pitch values. This same procedure was followed in calculating mean peak-to-peak roll and mean vertical displacement data.

The 5 gait cycle variables listed above (i.e., mean peak-to-peak acceleration, mean time in left and right stance phases, mean vertical displacement, mean pitch variations, and mean roll variations for repetitive gait cycles) were then compared for the previously injured and matched control individuals.

3. Results

3.1. Data fidelity—raw data correlations

All directly measured IMU data stream waveforms (i.e., gait segment IMU data captured at 128 Hz) strongly correlated with simultaneous Vicon data streams for both trauma patients and controls. This included vertical acceleration (controls: $r=0.992\pm 0.010$ SD, injured patients: $r=0.983\pm 0.024$ SD), vertical displacement (controls: $r=0.902\pm 0.059$ SD, injured: 0.884 ± 0.065 SD), pitch angular velocity (controls: $r=0.920\pm 0.059$ SD, injured: 0.935 ± 0.064 SD), and roll angular velocity (controls: $r=0.910\pm 0.101$ SD, injured: 0.977 ± 0.018 SD). Each aggregate correlation listed above is the result of comparing twenty individual waveform pairs (i.e., 20 gait segments for each group and each variable). Figure 2A and B provide graphic examples of Vicon versus IMU angular velocity data stream correlations of $r=0.8933$ and $r=0.9674$, respectively, for a single gait segment for patient 3 in our study. IMU data were subsequently used to calculate the parameters used in gait analysis.

3.2. Gait characterization

Table 2 presents gait variable data for the 5 trauma patients versus combined data for the control group, which demonstrates differences in L/R vertical acceleration and dual stance time (i.e., gait asymmetry and aperiodicity, respectively). As observed during testing, patients 1, 2, and 4 exhibited little or no gait pathology. Patient 3 presented with a noticeable limp and patient 5 demonstrated significant gait pathology. Links for online videos for representative 5-m gait segments for patients 1, 3, and 5 have

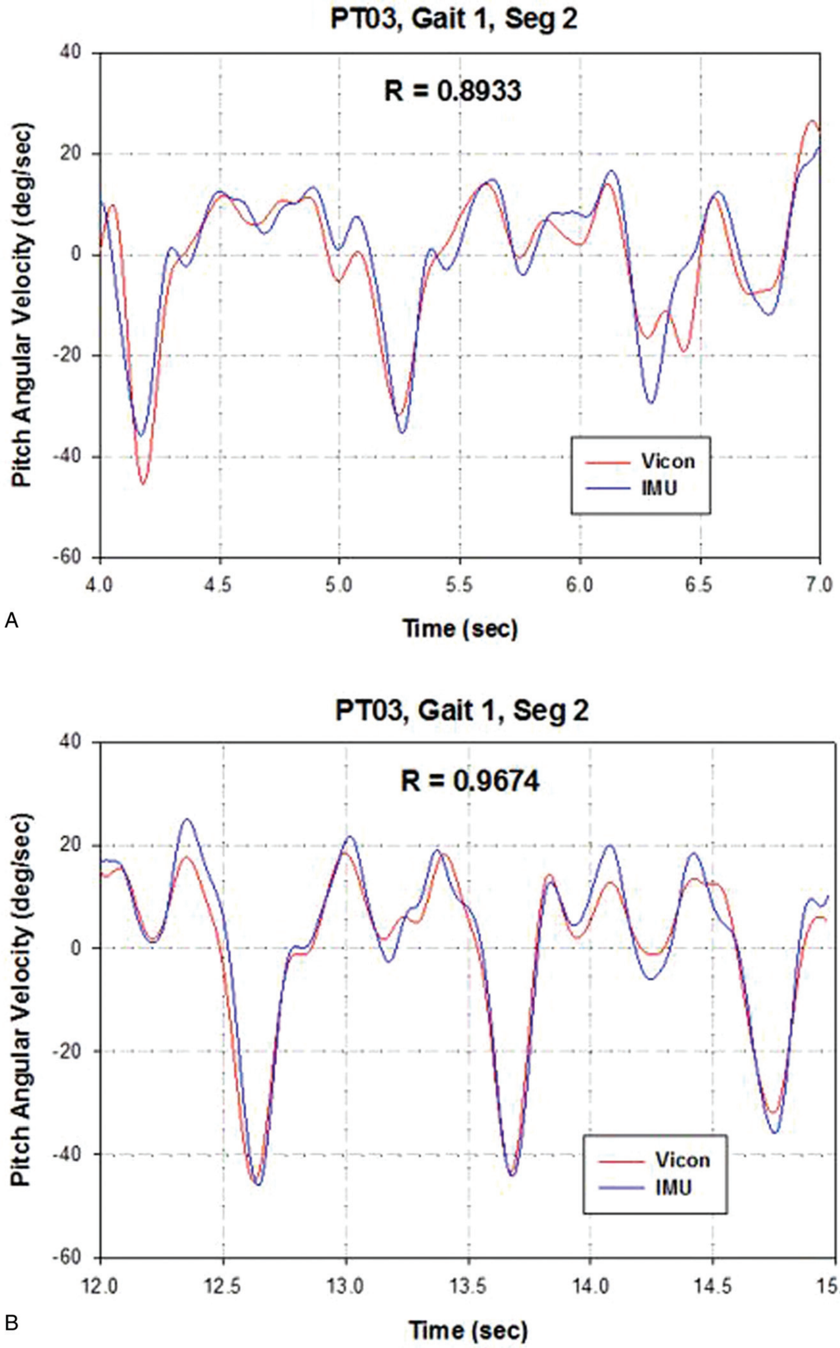

Figure 2. (A and B) Examples of raw data tracings comparing the data measured from the IMU versus the Vicon system measurements illustrating how relative differences in waveform data affect the correlation coefficients (i.e., "goodness of fit").

been provided as examples of progressive gait abnormality/pathology. Table 2 demonstrates the significant and increasing disparity in left versus right vertical acceleration and stance times with patients 3 and 5 (in gray) as compared with controls and with patient 1. For both of these variables, the affected limb demonstrated shorter stance times and lower peak-to-peak acceleration as compared to the unaffected limb (or less-affected limb in the case of multitrauma patients). As previously stated, vertical acceleration L/R differences and dual-stance to dual-stance time differences normalize the data against patient size and gait speed effects and accentuates functional disparities in the lower extremities on an individual patient basis. In an individual with normal gait, one would expect these differences to be very small (i.e., strides would be symmetric and periodic).

Table 3 compares individual patient peak-to-peak vertical displacement, pitch and roll values versus aggregate control values with significant differences shown as grayed table entries. While Table 2 deals primarily with lower extremity functional parameters, Table 3 provides quantitative data with regard to compensatory mechanisms of the upper body. Once again, patient 5 demonstrates significant gait pathology with regard to all upper extremity gait parameters, but differences for patient 3 for these absolute upper body measures are not readily apparent. This small data comparison set perhaps points out the need for

Table 2

Peak to Peak vertical accelerations (m/s2), stance time (ms) and corresponding asymmetries for combined controls vs individual patients.

	P2P vert acc		Vert acc	DS2DS time		DS2DS time
Subject	Left stance, m/s^2	Right stance, m/s^2	L/R diff., m/s^2	Left stance, ms	Right stance, ms	L/R diff., ms
Controls	7.46 ± 0.36	7.323 ± 0.396	0.13	520 ± 12	520 ± 12	0
1	5.78 ± 0.30	5.88 ± 0.40	0.10	523 ± 8	525 ± 11	2
2	4.46 ± 0.19	4.64 ± 0.16	0.18	593 ± 7	573 ± 4	20
3	6.55 ± 0.31	4.17 ± 0.22	2.37	609 ± 7	465 ± 10	144
4	9.94 ± 0.79	10.05 ± 0.67	0.11	519 ± 28	536 ± 11	18
5	8.02 ± 0.51	1.61 ± 0.51	6.41	693 ± 29	426 ± 8	267

P2P Vert Acc = Peak to Peak (+/−) Acceleration; indicative of vertical push off forces (L/R differences quantify asymmetry in L/R push-off forces regardless of patient size or gait velocity).
DS2DS Time = Peak Acceleration to Peak Acceleration (+/+) Dual Stance Intervals; (L/R differences quantify aperiodicity regarding mean time spent on each limb regardless of patient size or gait velocity).
Significantly different values from controls depicted in gray.

normalizing algorithms for these types of absolute measurements to increase their sensitivity to more subtle gait abnormalities.

4. Discussion

PBMs play a critical role in evaluating patient recoveries after trauma. Routine gait analysis has not been practical in the past, but the ability to objectively and reliably measure a patient's gait would be valuable. It could allow physicians to temporally measure a patient's progress toward recovery, compare their progress to other patients with similar injuries at similar time intervals, and compare their status to normal population controls.

The data from this study support the potential of a simple wearable IMU to fill that role. The results demonstrate that the technology is highly accurate and correlates extremely well with the same data measured using a more expensive and complex Vicon system, heretofore considered the gold standard for gait analysis in orthopaedic research.

Furthermore, *this IMU system* is able to capture and quantify clinically meaningful information. When subjectively assessing gait pathology visually, as is often done in the clinic, a trained observer may be capable of detecting asymmetries in stance times on each limb and exaggerations in upper body vertical displacement or angulation. However, these individual motions take place in time intervals measured in fractions of a second, and thus have been challenging to quantify without sophisticated equipment. This study demonstrates that with the use of a minimal amount of unobtrusive instrumentation (i.e., one chest-mounted IMU) clinically relevant data can be obtained capable of quantifying gait pathology, something that has heretofore been nearly impossible in a busy clinical setting. This technology allows a test to be performed within 5 minutes with minimal personnel or training requirements, which could potentially make routine gait analysis broadly available. While lower extremity measurements involving gait symmetry and synchronicity appear to provide the ability to delineate degree of gait abnormality and/or assess rehabilitative progress, upper body kinematic measurements would provide more information regarding types of gait patterns. These upper body measurements, however, appear to require further algorithm refinements to increase their sensitivity to more subtle gait changes.

Table 3

Peak to Peak vertical displacement (cm), pitch (deg) and roll (deg) for combined controls vs individual patients.

Subject	P2P vert disp, cm	P2P pitch, degree	P2P roll, degree
Controls	5.22 ± 0.14	4.47 ± 1.06	5.12 ± 1.45
1	4.20 ± 0.09	5.00 ± 0.36	6.30 ± 0.46
2	3.47 ± 0.17	7.67 ± 0.40	9.11 ± 0.61
3	5.98 ± 0.51	6.33 ± 1.06	7.94 ± 0.13
4	7.28 ± 0.08	4.94 ± 0.17	8.97 ± 0.50
5	9.15 ± 0.53	24.86 ± 0.66	15.26 ± 0.89

P2P Vert Disp = vertical displacement.
P2P Pitch & P2P Roll = forward/backward pitch and side-to-side roll angular displacements.
Significantly different values from controls in gray.

There are notable limitations in this study that require discussion. Our total sample size of patients with injuries is relatively low, and there is high variability in the pathology represented. However, the primary intention of this study was to provide a proof-of-concept that the IMU could capture meaningful quantitative information about gait that is accurate as measured by the existing VICON "gold standard"; it was not intended to make definitive statements about the nature, prognosis, or physiologic mechanisms of various limp or gait pathologies. Similarly, we chose to focus on a relatively narrow subset of gait parameters which are observable and used for gross clinical gait assessment but are not readily quantifiable. Certainly there is potential for more detailed analysis even with limited instrumentation. Additionally, although the data recorded by this system highly correlates to similar Vicon data, it only returns data for upper torso motion, and thus is only an indirect measure of lower extremity kinematics and does not capture as much data as a full video motion capture system analysis. However, we believe the relative cost and ease of implementation makes this approach highly suitable for routine use in a busy clinical setting. In addition, IMU applications return much richer and more nuanced data than other clinic-based performance measures as they are routinely collected currently, yielding only a single numerical result (i.e., total time to complete a test). Further, the IMU-generated variables selected for this study were shown to correlate with visualized clinical pathology both in real time and under slow motion video analysis, suggesting that evaluation of torso motion coupled with stance time data may be a reasonable proxy for lower extremity kinematic analysis, although future investigation is necessary. Measurements of gait symmetry and synchronicity appear to demonstrate particular promise for immediate and routine clinic use, while absolute upper body kinematic measures appear to require additional normalizing algorithms to increase sensitivity for subtle gait changes.

In conclusion, this wearable IMU system along with task-appropriate analytics represents a promising development for collecting accurate and clinically meaningful performance-based gait data for the orthopaedic lower extremity trauma patient population. The raw data can be easily obtained in a busy clinical setting, and correlates highly with data obtained from a Vicon system, the current gold standard. This system has the potential to make routine gait analysis in the clinical setting a reality and has multiple possible applications within orthopaedic surgery as well as for other specialties involved in neuromusculoskeletal care.

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