ELECTRONIC TEXTILES FOR IN SITU BIOMECHANICAL MEASUREMENTS

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ABSTRACT

This paper describes the benefits of and issues in designing and building an integrated, body-worn electronic textile (e-textile) system capable of assessing a suite of biomechanical measures. Unlike laboratory-based systems, this system would be worn by a soldier and could be used in a range of environmental conditions. A prototype e-textile developed at Virginia Tech has already shown promising results in the area of gait analysis.

1. INTRODUCTION

Among the many challenges confronting U.S. Army soldiers are increases in physical workload than can cause injuries, reduce performance, and ultimately threaten soldier survival. Comprehension of the biomechanical characteristics associated with combat maneuvers in the field can provide valuable information regarding injury mechanisms and optimal training protocols. However, field analyses of motion characteristics are infeasible utilizing currently available laboratory-based motion capture systems. E-textiles, fabrics that have the interconnections and electronics woven in, offer the possibility of creating a wearable system for monitoring and analyzing motion that has several advantages over laboratory-based motion analysis systems. An e-textile system does not require any external apparatus; the system is worn as a garment. Thus the e-textile system can be used for motion studies in the field and in everyday settings, unlike the artificial setting of the laboratory. The e-textile system can be used for studies in settings where it is impractical to set up external measurement apparatus, such as small tunnels. Another advantage is that the sensors in an e-textile system will be an intrinsic part of the garment, unlike, for example, retro-reflectors required for video-based motion analysis which must be attached to the subject and which protrude from the body. Consequently, an e-textile system will have a lower likelihood of interfering with the subject's normal motions. Because of these advantages, the e-textile system is particularly suited to biomechanical measurements in which subject has large areas of the body in contact with a surface (e.g., crawling), has to squeeze through tight spaces (e.g., entering or exiting vehicles or aircraft), or has to move through an environment with many obstacles (e.g., dense underbrush, rubble-strewn buildings).

2. RELATED WORK

The two main areas of related work are motion capture systems and e-textiles.

2.1 Motion capture systems

Because the e-textile prototype described in Section 4 is to be used for gait analysis, the focus of the related work in motion capture systems is on those systems intended for gait analysis.

Many of the advancements (in measurement) are motivated by new demands on our fundamental knowledge. The abilities to observe and interpret measurements of human movement have been the primary factors limiting growth of the field. Thus, the advancement of the study of locomotion remains dependent on the development of new tools for observation. Over the last few decades, there have been several fundamental advancements that have made a substantial impact on our understanding of the process of human locomotion.

Kinematic analysis measures the geometry of movement pattern without considering the forces that cause the movement. The majority of kinematic evaluations associated with gait analysis are performed using videographic or optoelectronic systems integrated with hardware and software system. Both of these systems involve marker application to subject, setting up and calibrating the reference frame, video or marker recording, digitization, transformation, smoothing and normalization. With currently available technology, digitization alone can take as much as 30 minutes for each five seconds of captured data (for more comprehensive information, please refer to (Sutherland, 2002)). Furthermore, preparation for the test, such as attaching a complete set of retro-reflectors for the motion capture system is a lengthy process, requiring approximately 30-60 minutes for a healthy young adult. The amount of time required and the complexity of the equipment make this a very expensive process, and use of these systems is

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usually confined to the laboratory due to the need for a hard-wired connection to the subject and/or controlled lighting conditions.

Various other types of motion sensors have also been developed in an attempt to assess gait characteristics in the field. These include pedometers, simple and low-cost devices that record the number of steps taken with varying degrees of sensitivity. Several types of accelerometers are also available. The advantage of these systems is that the device is small – and allows subject to wear the monitor for long periods of time without interfering with normal movement, and the ability to store data continuously over long periods of time. This information can then be analyzed to examine patterns of activity over the course of several days or weeks.

More recently, several investigators have used accelerometer to study dynamics of stability and kinematics of human gait. Yack and Berger studied the ratio of the even-to-odd harmonics of the accelerations (Fourier analysis) recorded at the second thoracic vertebra by a tri-axial accelerometer. The ratio of summed amplitudes of the even and odd harmonics was calculated for each stride and averaged across ten strides. This ratio was related to the smoothness of the gait (a larger harmonic ratio reflected a smoother gait pattern), and unsteady elderly subjects exhibited lower ratio.

A few authors (e.g., Kamen et. al. 1998, Moe-Nilssen 1998) have used accelerometers to study balance while standing quietly. Kamen et al. used two uniaxial accelerometers taped to the back (S2 level) and forehead of the subject and measured in the anterior-posterior (A/P) direction. They calculated RMS and frequency spectrum of the signals and performance parameters. Unfortunately this sensor configuration is affected by the acceleration of gravity, a function of the angle of the accelerometer with respect to the vertical. Moe-Nilssen used triaxial accelerometers to quantify balance during human walking. The average tilt of the sensor was used to subtract the static gravity error and then the data were transformed to a horizontal-vertical orthogonal coordinate system by a trigonometric algorithm. Root mean square was used on the data from each of the three axes as a performance parameter. This system has demonstrated test-retest reliability. Mayagoitia et al., recently presented a triaxial accelerometer- based system for determining the ability to maintain balance while standing by approximating the level of the center of mass. Their results suggested that the accelerometer measurements were sensitive enough to be able to distinguish between the different balance conditions using the force platforms.

Although short-term laboratory experimental sessions can accurately measure gait characteristic by directly measuring gait variables, intermittent activity in a field setting is much more difficult to assess. In that regard, Accelerometry has several advantages over traditional laboratory based system for gait analysis, primarily that it provides data over an extended period of time. For example, Kaufman et al., analyzed pathological gait and found that at least seven gait cycles are needed to obtain temporal data, but the results lacked precision. They actually needed 22 gait cycles to obtain precise temporal data. This long temporal recording could explain the good reproducibility (between and within-testers) in their results.

Improved routine analysis of locomotion depends on the development of new tools. The system must not introduce any artificial stimulus, and the ideal measurement system should encumber the subject minimally (Andriacchi et. al., 2001). In that regard, our e-textile gait analysis system could be an ideal system to provide kinematic gait analysis in clinical and research settings, but more importantly, in the field. We believe the gait analysis is the first step toward creating an e-textile garment for full body motion capture, one that is suitable for in situ biomechanical measurements.

2.2 E-textiles

The focus of this subsection is on a space-limited survey of related research in e-textiles, with an emphasis on systems related to health. E-textiles allow the creation of systems with a physical flexibility that cannot be achieved with existing manufacturing techniques, and consequently are a promising platform for wearable computing and health monitoring. Because e-textiles have the feel and appearance of normal cloth, they have several advantages over conventional electronics. Both the wires and the components are part of the fabric and thus are much less visible, and more importantly, not susceptible to becoming tangled together or snagged by the surroundings. **Consequently, e-textiles can be used in everyday situations where other electronics would hinder the user either in terms of movement or appearance.** With components available throughout the fabric, e-textiles also offer the possibility of greater redundancy and fault tolerance than conventional electronics, another advantage for everyday use.

The wearable motherboard project and related work at Georgia Tech has led to the creation of a system for monitoring a user's health, including heartbeat and respiration as well as the location of a bullet wound (Firoozbakhsh, 1999; Lind et. al., 1997). Applications include monitoring infants for Sudden Infant Death Syndrome as well as monitoring the status of soldiers on the battlefield. In these projects, wires were woven into the fabric for communication of data along with optical fibers to detect the location of bullet holes. Discrete sensors were attached and computing analysis was done outside of the garment. Further work at Georgia Tech has investigated the use of field programmable gate arrays

(FPGAs) as self-configuring, fault-tolerant switches. Recent NSF-funded work at UCLA has proposed the use of button-like devices on textiles for controlling and monitoring drug delivery (Estrin et. al.). A low-power, inexpensive computing environment has been proposed and simulated by a group at CMU (Marculescu et. al., 1997). An overview of much of this research can be found in (Marculescu et. al. 2003, and (Service, 2003).

In industry, a range of products is either on the market or under development. Philips has created a jacket that can sense the shape of the wearer's arms and torso and find the user's activity (Farringdon, et. al. 1999). ElekSen has developed a fabric keyboard that serves a dual-purpose in that it can be folded into a carrying case for a PDA device. This company has also developed fabrics for user interaction with vehicle interiors as well as health-care applications (Eleksen, 2004). **Durability tests show the fabric is as durable as a normal textile and that the sensing capability does not degrade over millions of user cycles.** Infineon has produced a wearable MP3 player (Jung et. al., 2002). The primary contribution in this work is a **method for packaging and attaching the digital and analog components in a washable, durable form factor** with pins at a suitable pitch for attachment to fabric.

3. E-TEXTILE DESIGN ISSUES

There are a number of issues that must be addressed in the design of wearable e-textiles for making biomechanical measurements, particularly related to sensor type and placement on the body. These design issues are difficult to explore via prototyping alone, and thus we have created a design and simulation environment for e-textiles that encompasses the physics of the user's movement, the behavior of the sensors, and the computing properties of the e-textile itself.

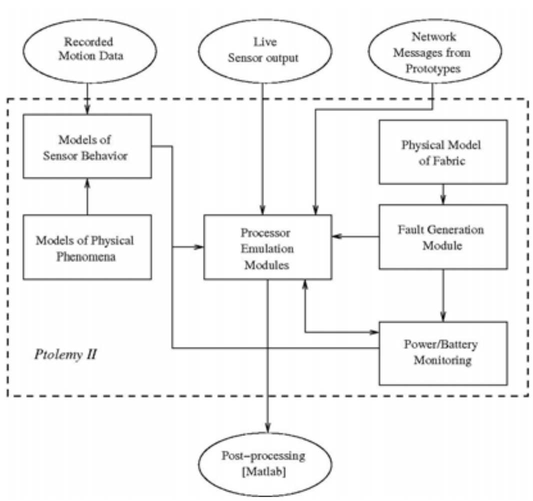


Figure 1. Tailor-Made simulation environment

A key feature of the gait analysis garment described in Section 4 is that it was designed using an e-textile design and simulation environment that we have developed, called Tailor-Made (Martin et. al. 2003). Tailor-Made accounts for human motion and models the physical behavior of sensors, allowing us to simulate sensor placement on the body and processing of sensor data, as well as the interaction of sensors with the physical surroundings. Thus we were able to explore a variety of sensor types, sensor placement, and algorithms for measuring motion before building the pants prototype.

The Tailor-Made modeling and simulation environment allows for detailed, accurate simulation of many aspects of e-textile operation, including sensor input, energy consumption, software execution, fault tolerance, and application behavior, as shown in Figure 1. The environment has been used to explore the design space for several e-textile applications, both wearable and non-wearable.

Figure 2 depicts the environment used in designing the prototype garment for this application. Using a database of body position data from a wide range of users and user activities, accurate models of different sensor types are used to generate simulated sensor time series data. The environment was used to develop a method to measure step length, a critical parameter in gait analysis (Edmison et. al. 2003). Simply double integrating the acceleration from the ankle accelerometers to calculate step length has an error of about 70%, due to the changes in the orientation of the accelerometers as the user goes through a walking motion and integration errors. Using Tailor-Made, we systematically developed a correction method that has an error of about 10%, as will be described in Section 4.

Our primary goal is to create an e-textile-based gait analysis system that has the same level as accuracy as laboratory-based methods of gait analysis. To meet this goal, several questions must be addressed.

- What is the level of accuracy that we can achieve with e-textiles and what are the engineering trade-offs between accuracy, cost, and ease-of-use?
- How does the accuracy of e-textiles compare to more expensive and more difficult to use laboratory set-ups?
- How does accuracy vary with fitting devices to an individual, i.e. this approach will be less feasible if the device has to be custom-fit to the patient, but it will be more feasible if we can provide a set of standard sizes.
- What is an appropriate design for the woven bolts of fabric that will allow the placement of sensors, actuators, and computing devices across a variety of garment sizes? Design for cost-effective

manufacture is of significant importance in the proposed research.

- What steps can be taken to improve the time between battery recharge of these e-textiles? Are there domain-specific characteristics that we can exploit to reduce power consumption? Can new fiber batteries be used to improve energy storage capacity in the garment?
- How do we ensure continued functionality over the lifetime of the garment? Small tears and wearing of localized areas is expected in any long-worn garment and should not lead to a failure, particularly an unidentified failure, of the sensing and computing capability of the fabric.

While simulation was used for initial exploration of these issues, we have constructed a working prototype to more fully understand the solutions required.

4. GAIT ANALYSIS PROTOTYPE

The Virginia Tech E-Textiles Laboratory and Locomotion Research Laboratory have a broad and extensive background in building e-textiles and conducting biomechanical studies, respectively. The pants constructed for this project will be based on the current context-awareness pants prototype developed by the VT E-textiles Laboratory. This prototype, shown in Figure 3, has wires woven into the fabric to carry power and data around the textile. The weave pattern is designed such that different sizes of pants can be cut from the same bolt of cloth while still retaining the capability to place sensors, processors, and communication elements where required. The textile has "floating" wires at regular locations across the fabric to allow for attachment of *e-tags*, electronic attached gadgets (Lehn et. al. 2004). An e-tag is a small printed circuit board with connectors specifically designed for attachment to textiles. A variety of e-tags have been designed and constructed by the VT e-textiles group; these e-tags use the wires in the fabric to draw power and communicate amongst themselves.

The e-textile pants developed for this project draws upon the e-tags technology while incorporating new battery fibers and sensors into the weave as they become available. The pants currently employ two types of sensors. Piezoelectric fibers will be used to measure angular velocity at a joint as well as a significant range of force values applied to an area (Martin et. al. 2003). Accelerometers can be strategically placed (e.g., hips and heel) to directly compute acceleration and, by integrating the results, indirectly compute velocity and distance traveled.

Using motion capture data from several individuals (Martin et. al. 2003), the Tailor-Made simulation environment was used to predict the accuracy of stride length computed by integrating the data from accelerometers placed on the ankles.

The results of the simulation indicate a significant difference in the true (ideal) acceleration and the acceleration measured by the simulated accelerometer (see Figure 4, top). When the velocity is calculated based on the ideal and simulated acceleration in Figure 4 (bottom), a significant error is introduced. When step length is computed based on this velocity (see Table 1) errors of approximately seventy percent are recorded. Closer examination of Figure 4, however, shows that the deviation in true and measured acceleration is limited to a small portion of the step. In order to calculate accurate gait metrics, it is necessary to compensate for the deviant acceleration. Fortunately, the deviation is generally

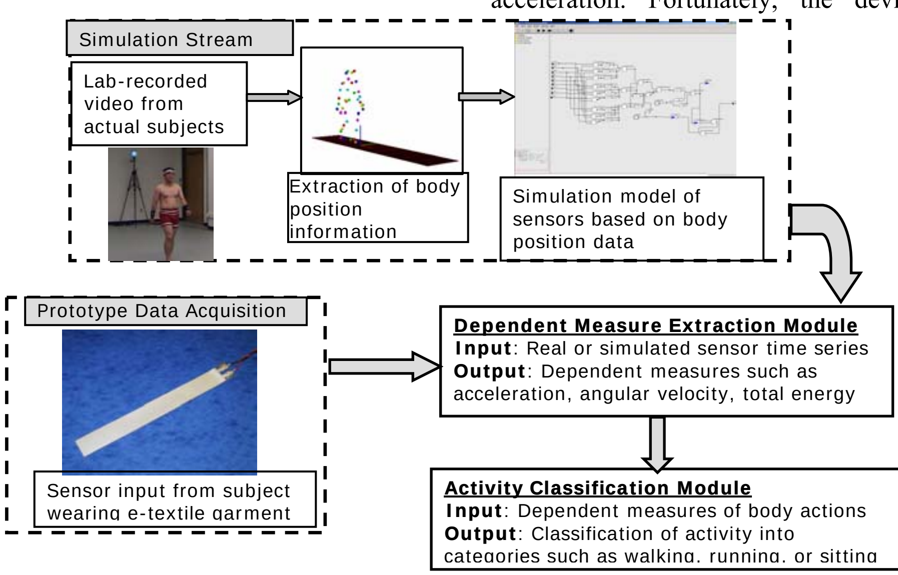
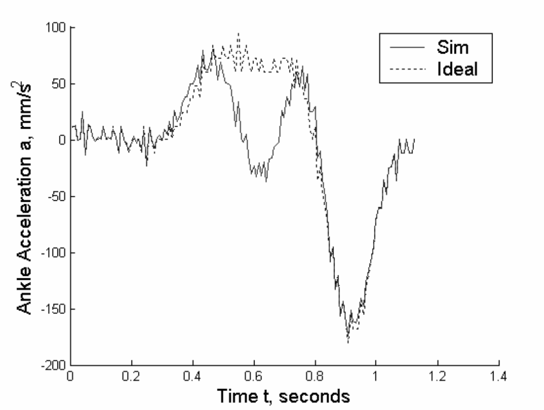


Figure 2. Design environment flow for e-textile pants

Figure 3. E-textile garment for gait analysis, showing fabric, sensors, and electronics

constrained to a single, small interval of the step and can be explained by the inherent biomechanics. The video data reveals that during this interval, the ankle is changing its angle with respect to the ground. This change in ankle angle is reflected in the accelerometer, causing it to no longer sense acceleration in a purely horizontal direction.

To compute a correction, we examine the biomechanics of a walking step. The basic biomechanics of a step dictate that the initial velocity and terminal velocity of a step must be approximately zero. The velocity curve calculated using the simulated accelerometer data shown in Figure 4 (bottom) has a terminal velocity that is non-zero. Given that we know the terminal velocity must be zero, we can correct for this error. The region of inaccuracy in acceleration is nearly identical in shape across all of the subjects in the motion capture data. By identifying this region and applying a correction to the acceleration that results in a terminal velocity of zero, we can closely match the correct acceleration. The correction is made by applying a three-point piecewise, linear fit across the affected interval of the ankle acceleration as shown in Figure 5 (top). The beginning, *x1*, and end, *x2*, of the affected interval are identified as peaks in the data. The height of the midpoint, *x3*, is chosen such that the terminal velocity computed from the acceleration is approximately zero. This piecewise linear data replaces the recorded acceleration in the deviant interval; the remainder of the acceleration data is retained unchanged.



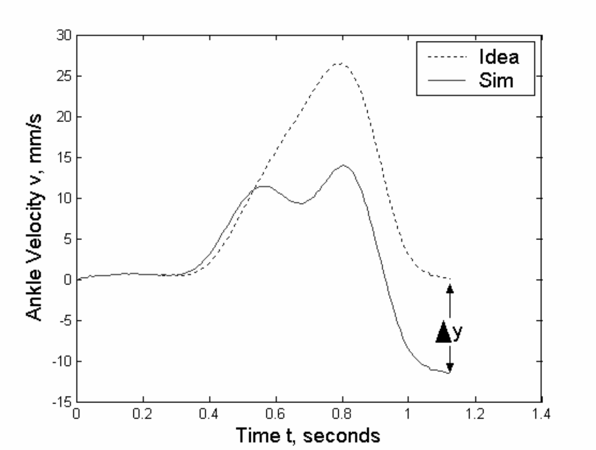


Figure 4. Top: Acceleration curves calculated using both position data and the simulated accelerometer incorporating the change in orientation of the sensor during walking. Bottom: Velocity curves calculated via integration from accelerations.

	Actual	Sim	Fit	Sim Err	Fit Err
(subject)	(mm)	(mm)	(mm)	%	%
Step 1 (1)	1097.4	341.2	1175.2	-68.9	7.1
Step 2 (1)	1084.4	413.6	1159.7	-61.9	6.9
Step 1 (2)	1180.6	271.3	1251.2	-77.0	6.0
Step 2 (2)	1172.4	318.7	1267.8	-72.8	8.1
Step 1 (3)	1220.8	312.5	1323.0	-74.4	8.4
Step 2 (3)	1234.1	303.6	1343.2	-75.4	8.8
Step 1 (4)	1410.3	299.6	1524.9	-78.8	8.1
Step 2 (4)	1411.3	512.2	1489.4	-63.7	5.5

Table 1. Step lengths for four subjects (two steps per subject) in simulation. Values are shown for the true distance as measured from position data, the values calculated from a simulated accelerometer, and the values calculated from the fitted curve used to correct the accelerometer. The percentage error in computed stride length from the simulated and fitted (corrected) accelerometer data is given.

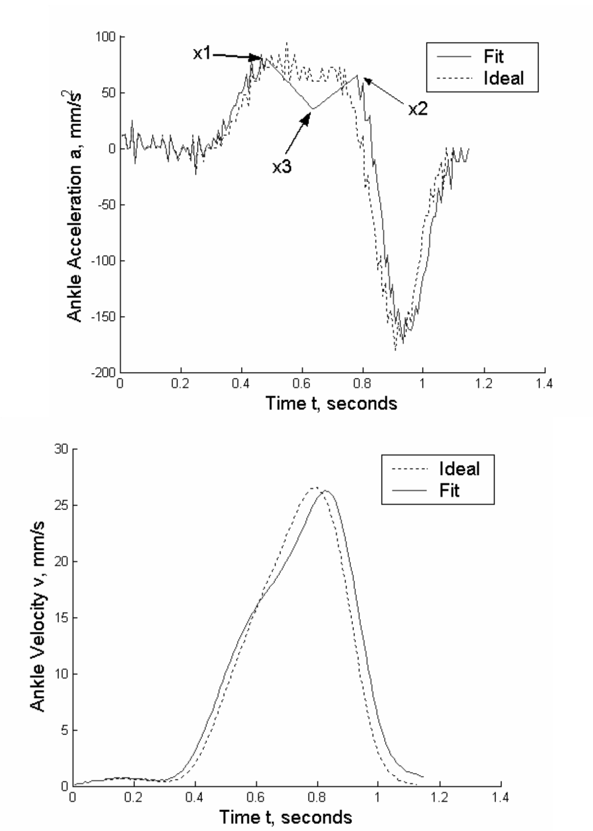


Figure 5. Top: Typical acceleration curves, both ideal and fitted using the described method above. Bottom: Typical acceleration curves, both ideal and calculated from the fitted velocity.

This new curve, when integrated to find velocity and step difference, is far more accurate as shown in Figure 5 (bottom). The step lengths for four subjects (two steps per subject) were calculated via simulation using the ideal motion capture position data, simulated accelerometer, and the accelerometer data corrected by the three-point piecewise linear fit method. The resulting calculations, shown in Table 1, using the fitted curve had an average error of 7% from the ideal value calculated from position data. Uncorrected acceleration data had an average error of 71%. To obtain preliminary validation of the operation of the e-textile prototype, an experiment was performed using five healthy, college-age subjects. Each subject wore the e-textile pants during a videotaped motion capture session and the data from each recording system was calibrated. The experimental setup consisted of two dual-axis accelerometers located on the ankles and piezoelectric strips affixed to the heels on the exterior of the subject's shoes. The accelerometers were oriented such that, in a standing position, they measure the horizontal and vertical components of acceleration. The piezoelectric films affixed to the heels were utilized to determine the precise step interval. Retro reflectors were placed on the hips, knees, heels, and toes. Two data sets (four steps) for a single subject were analyzed in the same manner used for the simulation data; the ideal step length was calculated using the position data from the video system and the fitted accelerometer data. The fitted accelerometer data was computed using the correction method described in the previous section. The step lengths from both the e-textile prototype and the video-based gait analysis system can be found in Table 2. The average error of 10.9% for these results was slightly larger than the simulation error of 7%. This variation can be attributed to noise, the use of a single size garment for a wide range of individuals, and the inability of the fitting algorithm to cope with unusual steps.

Another gait metric of importance is the heel strike velocity. The heel strike velocity is the instantaneous velocity of the heel 1/60th of a second before heel contact. Given that we were able to calculate step length via the double integration of accelerometers, it was reasonable to assume that the velocity curves obtained from a single integration were also valid. Using data from both the piezoelectric films attached to the heels and the accelerometers, heel strike velocities were calculated using both the e-textile prototype and the video-based gait analysis systems. Table 3 shows the results for the five subjects observed in the previous stride length experiment. The average error for these measurements was 7.2%.

While the results for measuring step length and heel strike velocities using the e-textile prototype appear to be reasonable given their amount of error, a more appropriate metric for evaluating measurement quality must be used. Based upon the analysis performed in (Henriksen et. al. 2004 and Shrout and Fleiss, 1979), the intra-class correlation coefficient (ICC) was utilized to examining relative reliability. For the step length, ICC was 0.698 and for the heel contact velocity ICC was 0.707. Using the criteria for acceptable clinical reliability developed in (Shrout and Fleiss, 1979) (ICC<0.4--poor; 0.4<ICC<0.75--fair or good, and ICC>0.75--excellent reliability) the reliability of the e-textile prototype for both step length and heel velocity was found to be satisfactory. It should be noted that in both experiments subject four exhibited significantly higher error than the other four subjects. Later review of the data revealed that this subject's gait consisted of a shuffle which was not handled well by the fitting algorithm. To correct for this, in the future we plan to include gyroscopes to compute the attitude of thigh, calf, and foot. In addition to the pants, we will be designing socks that incorporate the piezoelectric fibers to measure force applied at the heel and the ball of the foot, two measures critical to gait analysis.

Step Length (mm)			
Subject	Actual	Measured	Relative Error
1	1695	1464	-15.8%
1	1742	1623	-7.3%
2	1250	1509	17.2%
2	1248	1327	6.0%
3	1623	1671	2.9%
3	1564	1457	-7.3%
4	1485	1248	-19.0%
4	1479	1250	-18.3%
5	1759	1592	-10.5%
5	1440	1373	-4.9%
Average:			10.9%

Table 2. Step length from laboratory and measured using e-textile pants.

Heel Contact Velocity (mm/s)			
Subject	Actual	Measured	Relative Error
1	96.3	99	2.8%
1	84.2	83.02	-1.4%
2	39.2	38.4	-2.0%
2	37.9	37	-2.4%
3	60.29	56.86	-5.7%
3	58.24	53.93	-7.4%
4	45	54	20.0%
4	48	42	-12.5%
5	56.7	65.1	14.8%
5	49.2	47.6	-3.3%
Average:			7.2%

Table 3. Heel contact velocity from laboratory and measured using e-textile pants.

These preliminary results indicate that the pants, compare favorably to a state-of-the-art video system for two important gait parameters, stride length and heel contact velocity (Lockhart 2002). We are currently developing methods for calculating two other important gait parameters, the required coefficient of friction and the horizontal velocity of the center of mass.

To be useful for long term field studies and to decrease garment bulk and weight, one major design concern of the garment is power consumption. The system must also be able to trade-off the quality of motion sensing versus power consumption and performance requirements: Continuously sensing motion will increase the power consumption of the garment and unacceptably decrease the battery life. For example, the step length measurement indicates that there is a trade-off between the accuracy and the accelerometer sampling interval, as shown in Figure 6. The amount of processing required is inversely proportional to the sampling interval, and assuming that the power consumption of the sampling circuitry is small relative to that of the processor, the energy consumed is roughly proportional to the amount of processing.

Finally, the current simulation framework assumes that the garment fits tightly on the body and that processing/sensing elements on the garment do not move in relation to the body. However, for most garments, the cloth will drape over the body and move in relation to the body as the user moves about, changing the location of sensors relative to the body. Services and applications must be designed to account for this movement to be robust across a range of body sizes, motions, and garment types. Consequently, we plant to add draping and movement of cloth to the simulation framework, using existing tools intended for use in computer animated graphics and in the design of textiles (Adabala et. al. 2003).

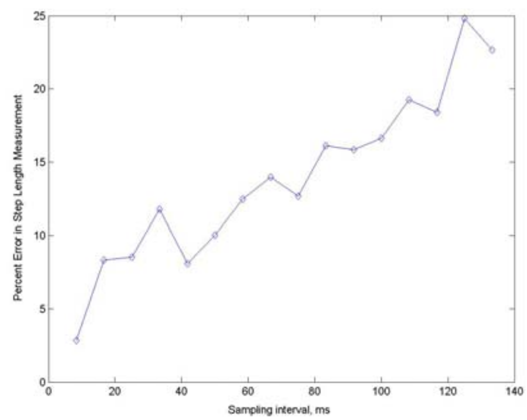


Figure 6. Step length accuracy vs. sample interval, indicating a trade-off between accuracy and sampling rate.

CONCLUSIONS AND FUTURE WORK

E-textile garments will enable the assessment of biomechanical parameters without requiring the subject to be in a laboratory environment. Interconnections and electronics are an intrinsic part of the fabric, thus permitting the implementation of a “smart” garment that can be worn in everyday settings. Consequently, an e-textile garment can assess a soldier’s movements in actual situations, such as in a vehicle or on the battlefield, in real-time. This will permit a better analysis of the effects of training, fatigue, and load carrying in operational environments, which is not possible with existing laboratory-based systems. We plan to design, via a combination of simulation and prototyping a more comprehensive motion analysis garment based upon our experience building the gait analysis pants prototype. This garment could be worn in place of normal uniform, or in conjunction with a uniform, and would not add significant weight to the subject or interfere with the subject’s motions in any way. The garment would monitor the forces acting on the subject's body as well as the subject's motions, and permit the analysis of gait and range-of-motion in response to the subject's load and environment. The garment would also permit the subject's motions to be measured over long periods of everyday activities, enabling the acquisition of data that would form the basis of accurate models of human motion.

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