

AN E-TEXTILE SYSTEM FOR MOTION ANALYSIS

Josh EDMISON¹, Mark JONES¹, Thurmon LOCKHART², and Thomas MARTIN¹
Electrical and Computer Engineering¹ and Industrial Systems Engineering²
Virginia Tech, 340 Whittemore Hall, Blacksburg VA 24061-0111, USA

Abstract. *Electronic textiles (e-textiles) offer the promise of home health care devices that integrate seamlessly into the wearer's everyday lifestyle while providing a higher level of functionality than current devices. Existing gait analysis systems are cumbersome laboratory-based systems that, while providing valuable information, would be difficult or impossible to deploy in the home. Yet gait analysis systems offer the promise of preventing and/or mitigating the serious effects of falls in the elderly population. This paper proposes an e-textile solution to this problem along with a design approach for realizing a solution that is inexpensive and usable across the elderly population. Preliminary results are given to demonstrate the promise of the proposed system.*

1. Introduction

An ideal home health care technology should be easy to use, reliable, and cost-effective, should blend in with the home environment, and should provide accurate medical information to the patient and/or caregivers. Wearable medical devices should be small, lightweight, and simple to attach, while medical devices that are used in the home should be easy to install and permit normal movement about the living space. A patient should be able to go about a daily routine without interference or distraction. Devices that do not have these characteristics will not be widely adopted or effective. In usability studies of health monitoring devices used by the elderly population, participants were apprehensive and lacked confidence in the devices due to the size, non-functionality when moving about, and lack of training [3]. An emerging technology, electronic textiles (e-textiles), holds the promise of creating home health care devices that will be more accepted and usable. In this paper, we outline an approach to investigating the use of e-textiles for monitoring and analyzing problems with an elderly person's gait, thereby reducing the risk of falling, a leading cause of mortality and nursing home placement.

E-textiles, fabrics that have electronics and interconnections woven into them, have the potential to provide home health monitoring and assessment that is small, lightweight, easy to use, and cost-effective. E-textiles allow the creation of systems with a physical flexibility and size that cannot be achieved with currently available electronic manufacturing techniques. Using standard techniques and machinery from the textile and garment industries, large e-textiles can be produced quickly and inexpensively, benefiting from the economies of scale of those industries.

Because e-textiles do not have wiring harnesses between discrete components, they have a distinct advantage over conventional electronics for home health care. Both the wires and the components are a 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 worn in everyday situations where currently available electronic devices would hinder or perhaps embarrass the user.

While we foresee numerous home health care uses for e-textiles, our focus in this paper is on using e-textiles to monitor and assess a patient's gait. An elderly person's gait is a good indicator of a number of medical conditions, including muscle weakness, strokes, and Parkinson's disease. A person with gait problems has a greatly increased risk for falling, which in the elderly population is a major cause of mortality and nursing home placement. In the U.S., accidents are the fifth leading cause of death in the older population (aged 65 and older), and falls make up the largest percentage of accidents (over 65%) for this age group [4]. Approximately 33% of the elderly population living at home will fall each year, and about 1 in 40 of them will be hospitalized. Of those admitted to the hospital after a fall, only about 50% will be alive one year later [5]. Additionally, falls and hip fractures among older individuals rank as one of the most serious public health problems in the U.S., with annual costs expected to exceed \$16 billion by the year 2040 [6].

Being able to analyze a person's gait easily, reliably, and cost-effectively would allow the medical community to reduce the incidence of falling in the elderly. However, with current technology, it is not feasible to assess a person's gait on a regular basis or in the patient's home. This paper addresses the problem through the design of e-textiles that can be worn by a patient or placed in the patient's home, allowing the patient's gait to be monitored and analyzed without interfering with a normal daily routine. In addition to monitoring and analyzing gait, this research will outline methods for reducing the severity of a fall as well as helping patients improve their gait.

In this paper, the authors outline the research issues associated with designing an e-textile system for gait analysis. The goal is to create an e-textile system that can provide the same level of accuracy as a video-based laboratory system, while being cost-effective and easy to use. An important aspect of the project is to quantitatively assess the accuracy of the e-textile system by comparing it to a video-based laboratory system. The measures that must be compared are kinematic and kinetic parameters of gait (i.e., stride length, stride width, lower extremity joint angles, friction demand, and joint torques), movement patterns associated with whole body Center-of-Mass (COM), and slip parameters (i.e., heel slip distances, and sliding heel velocity.) By creating an inexpensive gait analysis system that can be used in the home or in the doctor's office, other researchers will be able to more easily study gait-related problems at home and to use gait analysis as a diagnostic tool for predicting and mitigating fall accidents among the elderly.

In addition to being accurate, the e-textile must tolerate a range of faults, operate on a small energy budget, and be cost-effective to manufacture on existing textile equipment. By using a design process that incorporates high-fidelity simulation and prototype manufacturing [2], we will construct a weave pattern (including wire, sensor, and processor placement), textile network design, and sensor/processor activity level assignment that provides the required level of application accuracy, fault tolerance, and energy consumption. It is expected that the resulting experience and process will enable the construction of a wide range of e-textiles for home health care.

2. Gait Analysis

A review of the biomechanical literature indicates that there are several differences in the gaits of older and younger adults. Older adults tend to walk slower, have a shorter stride length, and a broader walking base. This results in a gait cycle with a longer stance or double support time [7]. On slippery floor surfaces, people of all ages tend to shorten their stride length to reduce horizontal foot forces and reduce the likelihood of slipping [8]. It is

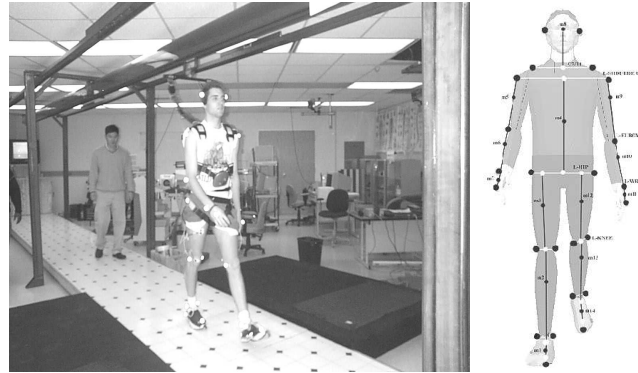


Figure 1. Picture from the VT Locomotion Research Laboratory showing a typical gait analysis apparatus. The field layout of the experiment includes a fall arresting harness and moveable force plates. Twenty-six reflective marker positions (two heel markers hidden on the illustration) are also illustrated.

generally believed that the shorter step length and the slower walking velocity of older adults result in a more stable or safer gait pattern, but these gait changes may also have some important implications for the initiation of slip-induced falls.

Initiation of a slip occurs whenever the frictional force (F_{μ}) opposing the movement of the foot is less than the horizontal shear force (F_h) at the foot during the heel contact phase of gait [9]. Specifically, at the time of the heel contact, there is a forward thrust component of force on the swing foot against the floor. This results in a forward horizontal shear force (F_h) of the ground against the heel. Additionally, a vertical force (F_v) occurs as the body weight and the downward momentum of the swing foot (and leg) make contact against the ground.

Lockhart et al. conducted a laboratory study to examine the gait changes associated with aging and the effect of those changes on initiation of slips, initial friction demand, and frequency of falls. The results indicated that older participants' horizontal heel contact velocity was significantly faster, and transitional velocity of the whole body COM (velocity changes between heel contact to shortly after heel contact phase of the gait cycle) was significantly slower than their younger counterparts. Slower transitional speed of the whole body COM increased horizontal foot force at heel contact, and increased friction demand at shoe/floor interface. As a result, older subjects slipped longer and faster, and fell more often than younger subjects.

At present, gait analysis is performed using a video-based locomotion laboratory. Retro-reflectors are attached to anatomically significant body positions on the patient, as shown in Figure 1. The patient is videotaped as he or she walks, and then the video is processed offline to compute an array of dependent measures used to characterize the gait. With currently available technology, this processing requires about 30 minutes for each five seconds of video. Donning a full set of retro-reflectors is in itself a lengthy process, requiring approximately 30-60 minutes for a healthy young adult; more time may be required for an elderly patient. The amount of time required and the complexity of the equipment make this a very expensive process, and a completely natural analysis is not possible in a laboratory. Consequently, locomotion laboratories are not commonly used as a diagnostic tool.

3. The Proposed System

Our aim to design an e-textile that is capable of computing the array of dependent measures associated with gait analysis with the same accuracy as computed by video-based gait analysis systems. This e-textile will consist of pants and either shoes or socks. Because of its simplicity, such an e-textile can be worn by the user in the home to provide for more realistic data for analysis as well as provide feedback to the user on improving gait. In addition, the system can detect the initiation of a fall and deploy a hip airbag designed in the Virginia Tech Locomotion Laboratory to mitigate the effects of a fall. Current hip protector technology utilizing soft and hard shell hip pads offer some reduction in the peak impact forces, but in most of the studies on hip protectors, compliance has been the biggest problem, with an average compliance rate range from 24% to 45%. Major reasons for not wearing hip protectors were: readily conspicuous, too unattractive and, too bulky and cumbersome to wear. A compact airbag activated during fall will provide better force reduction and, we hope, better compliance.

In addition to fall detection and mitigation, gait analysis can be used to detect a number of health problems. Many studies suggest that age-related changes in muscle strength have an important effect on fall accidents and physical performance capacities [14], and muscle strength degradation can be observed in gait. A frequent cause of difficulty in mobility in the elderly is an unreported or undetected cerebrovascular accident. The effects of severe loss of proprioception following a stroke on potential for recovery have recently been recognized [11]. A patient with significantly impaired proprioception after a stroke has marked muscular incoordination resulting in a disturbance of gait such as “wide-base-gait.” The clinical features of Parkinsonism in the elderly are akinesia, rigidity, tremor, postural impairment, and autonomic dysfunction, including dysphagia. Abnormalities of gait in Parkinsonism probably result from associated akinesia, rigidity, and effects in posture [11]. In addition to the above conditions, a number of other conditions may result in an impaired gait. These include dementia, peripheral neuropathy caused by diabetes or neoplasms, normal pressure hydrocephalus, undiagnosed foot problems, and unsuspected fractures of the hip.

To design an e-textile with these capabilities, 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.
- 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.

- How do we evaluate usability? Patients will not use the devices if they are difficult to put on or if the devices require training sessions to be accurate.

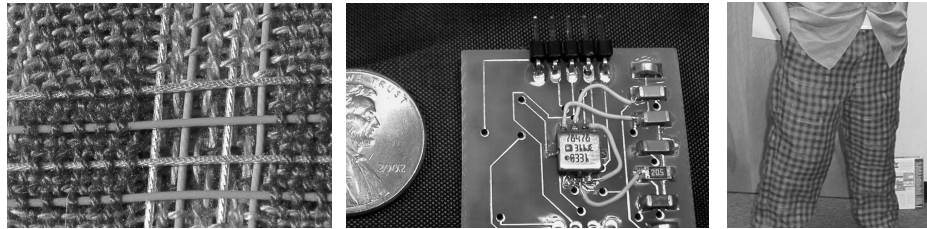


Figure 2. Virginia Tech shape-sensing pants: (a) orange and silver wires woven into the fabric, (b) prototype “e-tag” for attaching electronics to fabric, (c) final garment.

To answer these questions and construct our proposed e-textile, our approach is to use the Tailor-Made modeling and simulation environment [2] to explore the selection and placement of sensors on the human body for the gait analysis application, and then to create a set of prototype garments. The Tailor-Made modeling and simulation environment allows for detailed, accurate simulation of many aspects of e-textile operation, including sensor input, energy consumption, fault tolerance, and application behavior. In preliminary work, this environment has been used to develop an e-textile capable of extracting dependent measures such as acceleration of a joint, angular velocity of a joint, or stride length, and then using those dependent measures to classify the wearer's activity into categories such as walking, running, or sitting [2]. Developing this application requires making design choices such as the number, type, and position of sensors, the choice of dependent measure, and the frequency of sampling such measures. Designing a general garment requires making these choices in such a way as to be applicable to a large class of users rather than custom-designing a garment for a single user. Further, the classification algorithms should be trained to operate across a range of users as well. Using a database of body position data from a wide range of users and user activities [1], accurate models of different sensor types are used to generate simulated sensor time series data. For example, we constructed a mathematical model for the electrical response of a piezoelectric film when excited by the motion of the joint to which it is attached. After training the system on a range of simulated users, we then constructed a prototype garment and used the unmodified system to classify user activity based on the physical readings from the garment. Without re-training the classification algorithms, we were able to obtain 94% accuracy on classifying actual user activity using the prototype garment. This indicates a close match between simulation and physical behavior.

The pants constructed for this project will be based on the current context-awareness pants prototype developed by the VT e-textiles group. This prototype, shown in Figure 2, 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 (see Figure 2a) to allow for attachment of e-tags, electronic attached gadgets [13] (see Figure 2b). 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 [12][13]. We are currently considering three basic types of sensors for use in the pants to compute the dependent measures associated with gait analysis. Piezoelectric fibers can be used to measure angular velocity at a joint [2] as well as a significant range of force values applied to an area. 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 [2]. Finally, gyroscopes can be used 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.

4. Simulation Results

In this section, we use simulation to investigate the use of accelerometers placed on each ankle to compute the stride length of the user. While stride length is only one of the dependent measures, accurate computation of this will allow for other measures such as stride onset and completion as well as velocity at any point during the stride. Using motion capture data from several individuals [1], 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 3a). When the velocity is calculated based on the ideal and simulated acceleration in Figure 3b, 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 3a, 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 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.

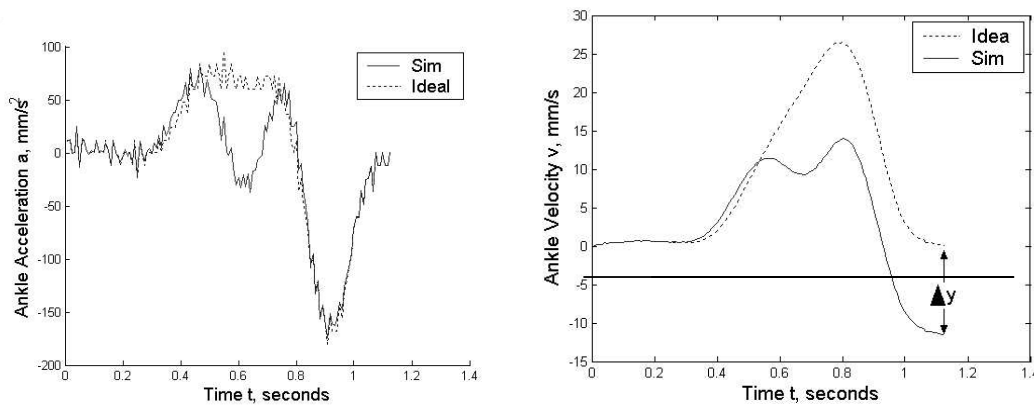


Figure 3. (a) Acceleration curves calculated using both position data and the simulated accelerometer incorporating the change in orientation of the sensor during walking. (b) Velocity curves calculated via integration from (a).

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 3b 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 4a. 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.

	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.

This new curve, when integrated to find velocity and step difference, is far more accurate as shown in Figure 4b. 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 Figure 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%.

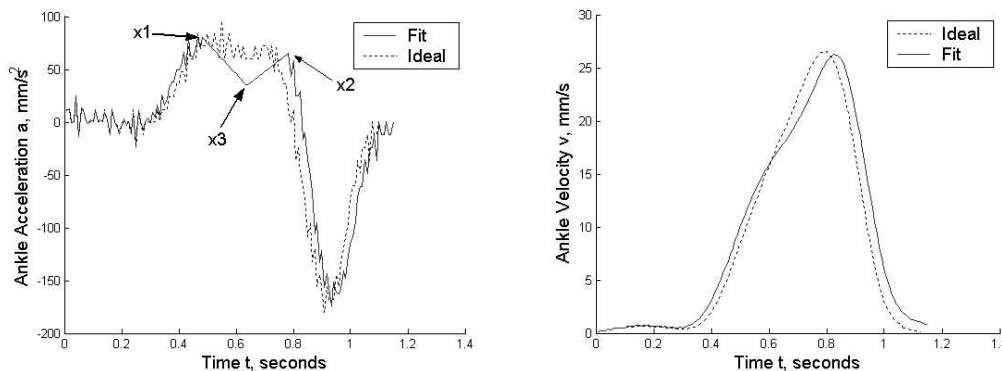


Figure 4. (a) Typical acceleration curves, both ideal and fitted using the described method above. (b) Typical acceleration curves, both ideal and calculated from the fitted velocity in (a).

5. Experimental Setup and Results

To verify these simulation results, the e-textile prototype pants used to compute context awareness were modified to compute stride length. A single user wore the 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 acceleration and velocity curves from the raw and fitted accelerometer are shown in Figure 5a and Figure 5b. The resulting step lengths for the first set of data exhibited error similar to that found with the simulation results, roughly 7%. The second set of step lengths averaged 0.85% error. The results for the measurements can be found in Table 2.

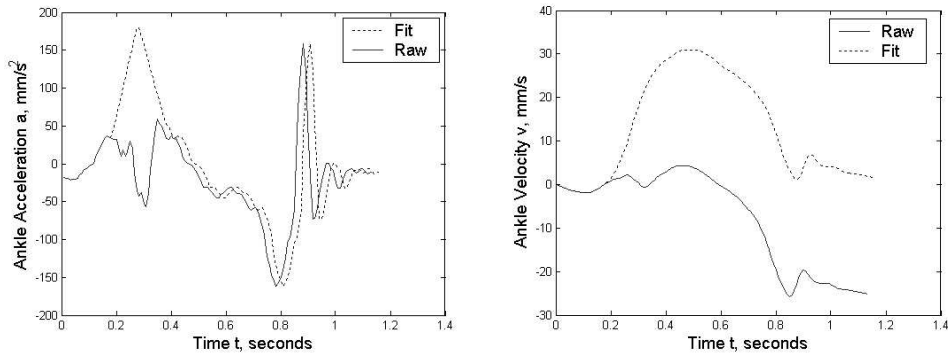


Figure 5. (a) Acceleration curves calculated from both actual accelerometer data and fitted accelerometer data using the method described above. (b) Velocity curves calculated from the actual accelerometer and from the fitted accelerometer data in (a).

	Actual	Fit	Err
(subject)	(mm)	(mm)	%
Step 1 (1)	1308	1407	-7.57
Step 2 (1)	1408	1311	6.89
Step 1 (1)	1333	1316	1.28
Step 2 (1)	1393	1383	0.72

Table 2. Stride length and associated error calculations using the e-textile pants as a data source.

6. Conclusions and Future Work

E-textiles offer a promising platform for a range of e-health applications. Advantages of e-textiles systems include increased user comfort, ease-of-use, ample surface area for sensors and communication devices, and cost-effective construction. This paper described a system

for gait analysis constructed with the intention of detecting pathological conditions as well as detecting and mitigating falls in the elderly. Results from an e-textile simulation environment were used to develop an initial prototype system for measuring one aspect of gait. Preliminary experimental results indicate that the resulting prototype system has a high accuracy.

Several challenges remain to be overcome before such a system is ready for field use. The next step in this process is computing a wider range of dependent measures including the force applied by different parts of the foot during a step and the velocity immediately preceding a step. In addition to computing a wider range of measures, the quality of the measurements must be assessed across a wide range of users, including those with pathological conditions and abnormal gaits.

7. Acknowledgements

This research was partially supported by NSF grant # 0219809 and by CDC/ K01-OH07450. The authors gratefully acknowledge Dana Reynolds and Eloise Coupey as the weaver and constructor, respectively, of the e-textile pants.

References

- [1] CMU Graphics Lab Motion Capture Database, <http://mocap.cs.cmu.edu/search.html>
- [2] Martin, T., Jones, M., Edmison, J., and Shenoy, R. "Towards a design framework for wearable electronic textiles," Seventh International Symposium on Wearable Computers, Oct 21-24, 2003, pp. 190-199.
- [3] Mann, W.C., Marchant, T, Tomita, M, Fraas, L, & Stanton, K., Elder acceptance of health monitoring devices in the home, *Journal of Long Term Home Health Care*. 20: 2, 2001-02, pp. 91-98.
- [4] National Safety Council, *Accidents Facts 1998 edition*. Itasca, IL. 1998.
- [5] Rubenstein, L.Z., Robbins, A.S., Schulman, B.L., Rosado, J., Osterweil, D., & Josephson, K.R., Falls and instability in the elderly. *J. Am. Geriatrics Society*, 36, 1988, pp. 266-278.
- [6] Sattin, R.W., "Falls among older persons: A public health perspective." *Ann. Rev. Pub. Health*, 13, 1992, pp. 489-508.
- [7] Winter, D.A. *Biomechanics and Motor Control of Human Movement*. 2nd Ed. John Wiley & Sons, Inc., 1990.
- [8] Cooper, J. M., and Glassow, R.B. *Kinesiology*. New York: Mosby Company, 1963, pp. 140-175.
- [9] Perkins, P.J., and Wilson, M.P. Slip resistance testing of shoes - New developments. *Ergonomics*, 26(1), 1983, pp. 73-82.
- [10] Lockhart, T.E., Woldstad, J.C., and Smith, J.L., Effects of age-related gait changes on biomechanics of slips and falls. *Ergonomics*, 46:12, 2003, pp. 1136-1160.
- [11] Cunha, U.V. "Differential diagnosis of gait disorders in the elderly," *Geriatrics* vol. 43, 1988, pp. 33-38.
- [12] Nakad, Z., Jones, M. and Martin, T. "*Communications in Electronic Textile Systems*," The 2003 International Conference on Communications in Computing (CIC 2003), June 2003, pp. 37-43.
- [13] Lehn, D., Neely, C., Schoonover, K., Martin, T. and Jones, M. "e-TAGs: e-Textile Attached Gadgets," Proceedings of the Communication Networks and Distributed Systems Modeling and Simulation Conference, January 2004, to appear.
- [14] Bonder, B.R. and Wagner, M.B., *Functional Performance in Older Adults*. Philadelphia: F.A. Davis Company., 1994.