Innovation: Changing the Face of Disability

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Approximately 650 million people in the world suffer from some type of disability and as the population ages this figure is expected to increase. Those afflicted with a physical, emotional or cognitive disability face a myriad of serious and debilitating challenges. Fortunately, the modern explosion in scientific and technological innovations provides an extraordinary opportunity to deliver profound improvements to their quality of life. Moreover, the same cutting-edge technology that can minimize or eliminate the adverse effects of disabling conditions can also be used to expand human abilities and transcend the ordinary limits of the human condition.

At the Massachusetts Institute of Technology's (MIT) Media Laboratory, the Biomechatronics Group and the Affective Computing Group are focusing on developing novel technologies that can deeply impact people's lives at the physical and emotional levels. The Biomechatronics Group seeks to understand the basic principles of biological locomotion in order to develop both rehabilitation technologies that restore functionality to the physically challenged and augmentation technologies that amplify the physical capabilities of healthy able-bodied individuals. The Affective Computing group works towards the development of technologies to expand our understanding of affect and its role in the human experience, with a focus on autism research and therapy. The interdisciplinary nature of the work of both groups integrates a broad gamut of disciplines, ranging from medicine to engineering.

The Biomechatronics Group and Affective Computing Group are part of MIT's Human 2.0 initiative to mitigate the effects of disability and redefine the limits of human capability.

BIOMECHATRONICS: DISABLED PEOPLE OR DISABLED TECHNOLOGIES?

Though often taken for granted, walking remains essential in modern life, as stairs, uneven terrain, and other obstacles easily conquered by legs but not wheels remain ubiquitous. The loss or disability of a leg tremendously impacts quality of life and patients strive to regain or retain the ability to walk even in the presence of severe impairment.

In the United States there are more than 26 million people with physical disabilities including more than 1.7 million (more than 1 in 200) living with limb loss (NLLIC, 2008). In order to restore lost limb functions, prosthetic and orthotic technology is generally required. The need for rehabilitation and prosthetic technology is latent, as the total number of persons with an amputation and using a prosthesis is expected to reach 2.4 million by the year 2020 (Ziegler-Graham, 2008).

Currently commercially-available technologies for lower limb amputees are still far from providing fully functional replacements of biological legs. Even with the most advanced prosthetic systems available on the market, amputees still exhibit clinical problems associated with lack of adequate mobility. These include gait asymmetry, instability, decreased walking speeds and higher energy requirements. Together these gait pathologies result in significant pain and walking fatigue for lower limb amputees (Postema *et al.,* 1997).

Although the pain felt at the residual limb corresponds to the behavior of the entire prosthetic system (i.e. from the liner and socket interface to the pylon and the rest of the prosthetic components), it is particularly associated with the coupling between the residual limb and the prosthetic leg. The imperfect coupling allows relative motion between the socket and the femur stump caused by the compression of soft tissue. This motion is uncomfortable for the amputee and causes a lack of confidence to apply large forces to the prosthetic leg. In addition, the relatively short moment arm between the hip joint and the socket reduces the force that the hip muscles can apply to the artificial limb (Whittle, 1991).

Recent advances in socket technology have reduced pain in patients by focusing on cushioning, a primary contributor to comfort. Such technologies cover a large spectrum, from gel liners and vacuum-assisted sockets to modern interfaces that rely on residual limb laser scanning and computer-aided manufacturing. Two particular technologies that have proved to be successful in pain reduction have been shock absorbing pylons and dynamic elastic response (DER) prosthetic feet (Perry *et al.,* 1992). The damping and compliance features they provide have made them popular in most of the commercially available prosthetic systems. Despite their success in preference among amputees, abnormal gait patterns and associated with walking fatigue are still prevalent.

Walking fatigue is synonymous with higher metabolic expenditure and is a common affliction of lower-limb amputees. Walking fatigue in lower-limb amputees is considerably higher than in their matched able-bodied counterparts at comparable speeds. Measures of metabolic expenditure during walking are commonly obtained by analyzing oxygen level consumptions. For unilateral below-the-knee amputees, the rate of oxygen consumption is 20-30% higher (Herbert *et al.,* 1994; Molen, 1973) than that for healthy persons with no impairments, and for above-knee amputees this rate increases by an additional 25% (James, 1973; Waters and Mulroy, 1999).

Conventional lower-limb prostheses, despite their damping and compliance features, have not provided a real metabolic advantage for amputees (Lehmann *et al.,* 1993; Torburn *et al.,* 1990; Colborne *et al.,* 1992; Huang *et al.,* 2000; Thomas *et al.,* 2000). In addition to higher energetic requirements, lower-limb amputees show a reduction in their self-selected speed, and in consequence they present overall diminished endurance.

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Prosthetic systems ideally need to fulfill a diverse set of requirements in order to restore the biological behavior of normal and healthy limbs. For the Biomechatronics Group, the biomechanics of normal walking provide a basis for the design and development of new actuated artificial limbs. This unique biomimetic approach to the design and development of these prostheses shows promise in improving amputees' gait symmetry, walking speed and metabolic requirements while enhancing the adaptation to the particular amputee's gait.

One of the objectives of the Biomechatronics Group is to develop sophisticated modular biomimetic leg prosthesis for lower-limb amputees that is capable of restoring the functionality of the ankle and knee joints of the intact human leg and fully emulating their natural behavior. This task poses many challenges for researchers as they investigate novel electromechanical designs and control strategies that can adequately integrate and adapt to the patients' needs. The complete robotic lower l3 limb is comprised of two modular robotic joint prostheses: a powered ankle-foot and robotic knee prosthesis.

Robotic Ankle-Foot Prosthesis

The human ankle joint is essential to locomotion because it provides a significant amount of energy to push the body off the ground and propel it forward during walking, especially at moderate to fast speeds (Winter, 1983; Palmer, 2002; Gates, 2004). For transtibial (below-the-knee) amputees, the loss of this energy generation at the ankle produces an abnormal asymmetric gait, with higher metabolic energy requirements and slower speeds. Additionally, the mechanical behavior of commercially available ankle-foot prostheses greatly differs from that of a healthy human ankle-foot. Even though most of these prostheses offer some compliance and function as initial and terminal rockers due to their shape, they cannot provide the amount of external energy required in walking, making them inadequate in replicating the natural ankle's flexibility and actuation (Whittle, 1991).

In order to overcome the disadvantages of current prosthetic technologies for below-knee amputees, the Biomechatronics Group has developed the world's first robotic ankle-foot prosthesis that can successfully recreate the actions of the biological lower leg (Au and Herr, 2006; Au *et al.,* 2007). Using advanced biologically-inspired design and intelligent computer algorithms, this novel device can propel an amputee forward while easily adapting to changes in ambulation speed and the walking environment. This artificial ankle-foot prosthesis allows amputees to enjoy a natural human gait over level ground, stairs, ramps, and even uneven terrain. Moreover, the device's low weight and biological form-factor make it comfortable to wear and inconspicuous to even the trained eye. Most importantly, this innovative device reduces the rate of oxygen consumption in walking amputees by up to 20% relative to conventional prosthetic devices (Au *et al.,* 2009).

The success of the active ankle prosthesis derives from the Biomechatronics Group's commitment to biomimetic design. The mechanical design of this motorized device imitates the biological structures of the ankle joint by using elastic elements and flexible materials in similar roles to those of the tendons and ligaments of the human joint. This exploitation of elastic elements reduces the weight of the necessary motor and minimizes the overall power that this battery-operated system requires, allowing an amputee to walk all day on a single charge.

This cutting-edge bionic research device has been so successful that it was awarded *Time Magazine*'s Best Invention of the year in 2007 and led to the creation of iWalk LLC., a start-up company commercializing this prototype.

Robotic Knee Prosthesis

For above-knee amputees, a particular source of pathological gait while wearing conventional prostheses is the lack of accurate control of the knee joint, particularly while the leg is swinging during each step. The knee cannot be allowed to swing freely because it will extend too rapidly and stop suddenly as it reaches full extension. On the other hand, the knee joint cannot be so rigid that it does not bend in response to dynamics; such rigidity would result in a large increase in the amount of energy required by the patient to go from one step to the next. To prevent these extreme cases, several prosthetic knees that behave as dampers (e.g. energy-dissipation mechanisms) have been developed using friction, hydraulic, pneumatic, or electro-mechanical systems. Some have been designed as variable damping devices which adapt to angle, speed and direction of motion. These mechanisms have partially addressed abnormal gait patterns in amputees (Whittle, 1991), but have not yet been able to mimic fully the complex behavior of the knee joint.

Building on the work that led to the world's first powered ankle, the Biomechatronics group has continued its line of innovation in bionic limbs by developing a state-of-the-art robotic knee

Figure 1. Biomechatronics' Robotic Ankle-Foot Prosthesis (*photograph by Webb Chappell ©MIT Media Lab*) and most recent prototype by iWalk, LLC.

joint prosthesis which overcomes the limitations of conventional prosthetic knees. This prosthesis is capable of replicating the behavior of the biological knee joint while seamlessly interfacing with the powered ankle, producing a full artificial lower-limb prosthesis (Martinez-Villalpando *et al.,* 2008; Martinez-Villalpando and Herr, 2010).

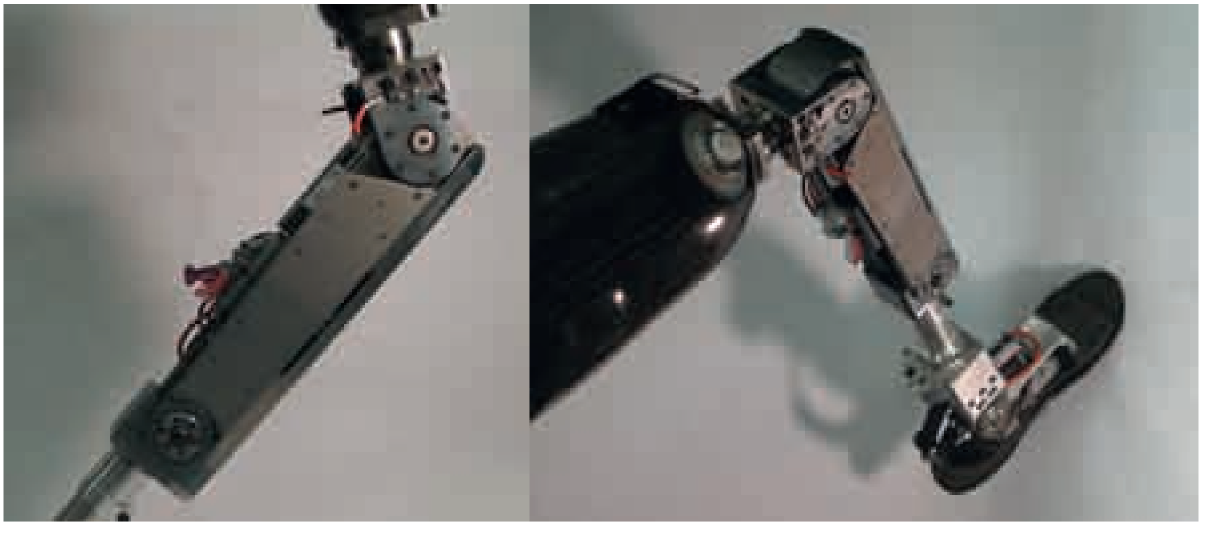
The active knee prosthesis is a novel motorized device with a unique biomimetic electro-mechanical design. The artificial knee mimics the functionality of the musculo-skeletal structures around an intact biological knee joint, producing a system that, like the artificial ankle, is small, light-weight, and efficient. Its design incorporates a microcomputer and a sophisticated sensory suite that enables an artificial intelligence capable of inferring the intentions of the amputee. The advanced design and control of this prosthesis aims to improve amputee gait beyond what other commercially available prostheses can offer, not only while walking on even ground but also while traversing difficult terrain, including ramps and stairs. The integration of the robotic knee and ankle prosthesis into a single prosthetic system yields the world's most advanced powered artificial lower limb for transfemoral amputees. Together, the active knee and ankle are expected to have great clinical impact while their novel architectures contribute to the development of future integral assistive technologies that adapt to the needs of the disabled.

Exoskeletons

Physical disabilities that often result in leg weakness include lower-extremity amputation, spinal-cord impairment (SCI), multiple sclerosis (MS) and stroke. For individuals who have suffered partial leg paralysis resulting from neurological pathology, the use of exoskeleton technology will offer a dramatic improvement in mobility capabilities over conventional leg orthotic technology.

The Biomechatronics group is leveraging its understanding of human locomotion and its experience in prosthetic limb design towards the development of exoskeletons (Walsh *et al.,* 2006; 2007). These wearable assistive structures help augment human mobility, increase human endurance and

Figure 2. The Biomechatronics Groups' Robotic Knee Prosthesis



assist physically-challenged persons. The group's walking exoskeleton is an orthotic system that works in parallel to the body, transmitting forces between the ground and the user's torso during standing and walking, effectively reducing the portion of body weight borne by the legs and making it easier for a disabled person to stand and to walk. Because the exoskeleton offers support normally provided by biological legs, physically disabled people suffering from leg weakness may walk with confidence while wearing it (Dollar and Herr, 2007, 2008).

In particular, the exoskeleton work developed at Biomechatronics Group looks into the passive dynamics of human walking in order to create lighter and more efficient devices with three specific goals in mind. Firstly, the exoskeleton currently under development aims to be the first wearable system that demonstrates a reduction in human energy usage during walking. Secondly, the exoskeleton should serve in potentially life-saving occupations, increasing the user's endurance while reducing damaging loads on the knee and ankle. These potential users include active soldiers and firefighters, among others, who perform activities that require brisk movement over varying terrain while burdened with significant loads. Finally, this technology aims to assist impaired human mobility. This exoskeleton architecture could be modified into a walking orthosis which permits an active lifestyle by reducing load on injured joints while providing the necessary support for normal walking to patients with otherwise limited mobility.

Figure 3. The Biomechatronics Group's load-carrying exoskeleton

AFFECTIVE COMPUTING: THE AUTISM CHALLENGE

Autism Spectrum Disorders (ASD) are a collection of neuro-developmental disorders characterized by qualitative impairments in socialization, communication, and circumscribed interests, including stereotypical behavior patterns and behavioral rigidity to changes in routines (APA, 1994). Current studies of ASD suggest a rate as high as 1 in 110 in children by the age of 8 years in the United States (CDCP, 2009). ASDs typically manifest in infancy and persist throughout the lifespan. These disorders have a profound impact on families and often result in enormous emotional and financial costs. For instance, recent estimates suggest that the societal costs in the United States to care for all individuals diagnosed each year over their lifetime approaches $35 billion (Gantz, 2007). ASDs clearly represent an emerging public health problem (Newschaffer *et al.*, 2003).

Through the Affective Computing group and the Autism and Communication

Technology Initiative at the MIT Media Laboratory, a variety of innovative technologies are being developed to better understand and support individuals with ASD in natural environments. Three of these applications, briefly reviewed in the following paragraphs, include: 1. automatically detecting stereotypical motor movements using wireless accelerometers and pattern recognition algorithms; 2. developing unobtrusive, wireless measures of physiological arousal; and 3. creating a suite of wearable, wireless technologies that enable the capture, real-time analysis, and sharing of *in situ* social-emotional cues from faces, voices, and gestures of self and/or interaction partners.

Sensor-Enabled Detection of Stereotypical Motor Movements

Stereotypical motor movements (SMMs) are generally defined as repetitive motor sequences that appear to an observer to be invariant in form and without any obvious eliciting stimulus or adaptive function. Several SMMs have been identified, the most prevalent among them being body rocking, mouthing, and complex hand and finger movements (Lewis and Bodfish, 1998). SMMs occur frequently in people with mental and developmental disabilities, genetic syndromes (Bodfish *et al.,* 2000), and less frequently in normally developing children and adults.

While investigations of ASD have increased in recent years in response to growing awareness of the high prevalence rates, the majority of this work focuses on social and communication deficits, rather than on restricted and repetitive behavior. This is a potential problem given the high prevalence of SMMs reported in individuals with ASD. Also, when severe, SMMs can present several difficulties for individuals with ASD and their families. First, persons with ASD often engage in SMMs. Preventing or stopping these movements can be problematic as individuals with ASD may become anxious, agitated, or aggressive if they are interrupted (Gordon, 2000). Second, if unregulated, SMMs can become the dominant behavior in an individual with ASD's repertoire and interfere with the acquisition of new skills and the performance of established skills (Koegel and Covert, 1972). Third, engagement in these movements is socially inappropriate and stigmatizing and can complicate social integration in school and community settings (Jones *et al.,* 1990). Finally, SMMs are thought to lead to self-injurious behavior under certain environmental conditions (Kennedy, 2002).

To better measure, understand, and remediate this complex class of behavior, we are developing an innovative system for automatically recognizing and monitoring SMM. Our system uses a miniature sensory suite that is comfortably worn on an individual's wrists and torso and transmits motion data to a mobile phone. Pattern-recognition algorithms running on the phone receive these motion data streams wirelessly, compute a variety of characteristic features, and automatically detect SMM topography, onset, offset, frequency, duration, and intensity (Munguia-Tapia *et al.,* 2004). Currently, this system has been able to correctly identify stereotypical body rocking, hand flapping, and head hitting approximately 90% of the time across six individuals with ASD in both laboratory and classroom settings (Albinali *et al.,* 2009).

There are several potential benefits associated with this novel system. Easily automating SMM detection could free a human observer to concentrate on and

Figure 4. The MIT's 3-axis wireless-accelerometer sensors housed in plastic cases with external battery holder. The cases can be worn on the wrists using elastic armbands.

note environmental antecedents and consequences necessary to determine what functional relations exist for this perplexing and often disruptive class of behavior. The system could also be used as an outcome measure to facilitate efficacy studies of behavioral and pharmacological interventions intended to decrease the incidence or severity of SMM. Finally, with minor modifications, the system could be programmed to serve as an intervention tool by providing real-time feedback to individuals with ASD and/or their caregivers when SMMs are detected.

Unobtrusive, Wireless Measures of Physiological Arousal

The Autonomic Nervous System (ANS) is a control system in the body with far-reaching influences, including maintenance of heart rate, digestion, respiration rate, and perspiration that mediates regulation of emotion, shifting of attention, sleep, signaling of anticipation and salience, biasing of memory, and more.

A number of investigators over the past thirty years have recorded ANS activity in individuals with ASD to assess physiological responsivity during attention and habituation tasks, while exposed to social and sensory stimuli, and when engaged in self-injurious and repetitive behaviors. Unfortunately, however, there are several methodological issues associated with these studies that cast doubt on the reliability, validity, and generalizability of the data obtained. For instance, the majority of ANS studies to date use obtrusive equipment that requires individuals to sit still while multiple wires are adhered to their chest or fingers, limiting the number of participants who can comply with the procedures and thus contribute data to a study. ANS observations are also undertaken primarily in unfamiliar research laboratories that are potentially stress-inducing, and are often limited to short intervals of measurement that may or may not represent a person's true ANS patterns when going about everyday activities. Data from these studies are also often averaged across persons so that no individual profiles are retained, obscuring the heterogeneity of response patterns across individuals.

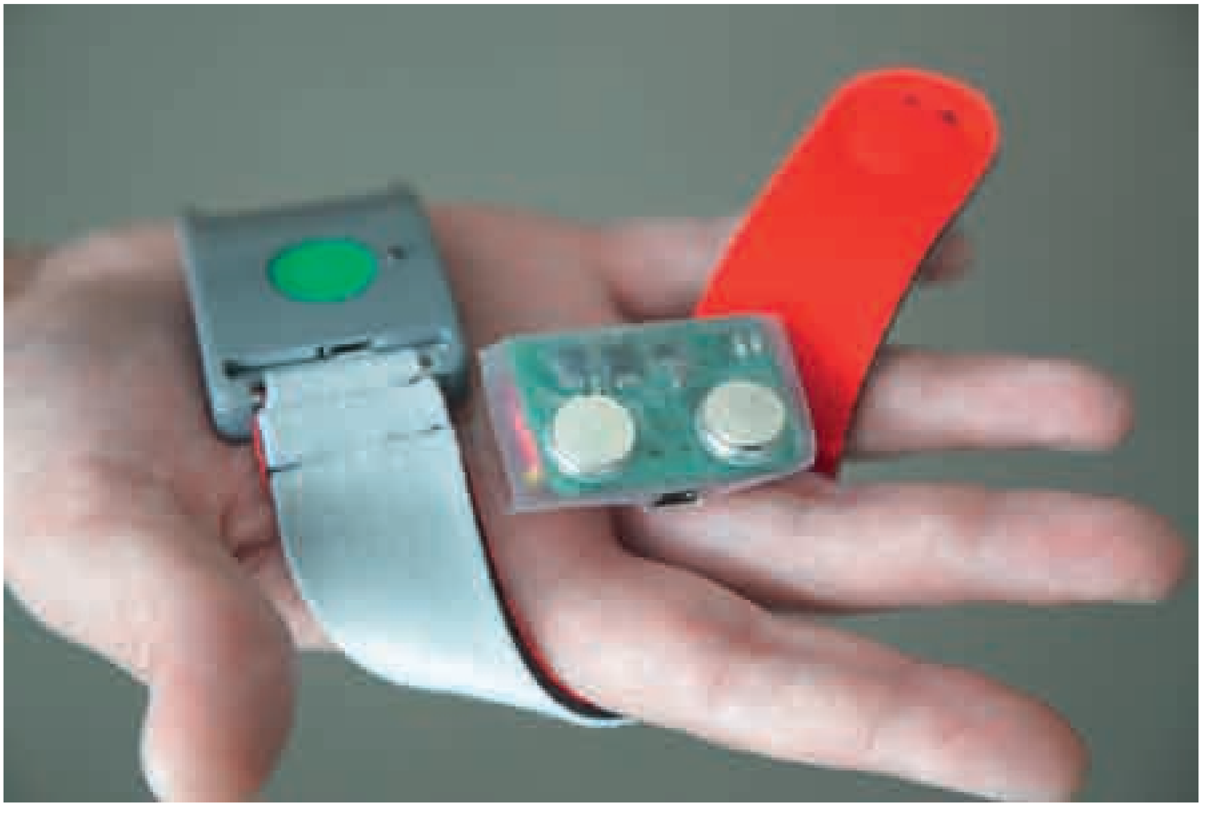
To overcome some of these methodological problems, a novel technology platform is being developed for sensing sympathetic and parasympathetic autonomic data comfortably off the wrist and ankle without wires or boxes (Fletcher *et al.,* 2010; Poh *et al.,* 2010). The system captures: 1. electrical conductivity of the skin, which provides a sensitive measure of changes in sympathetic arousal associated with emotion, cognition and attention; 2. heart rate and heart rate variability that provides information related to the sympathetic and parasympathetic branches of the ANS; 3. temperature; and 4. motor movement and posture changes through 3-axis accelerometry. The 3-axis accelerometer and temperature sensors provide information about a person's activity and account for the influence of motion and environmental temperature on electrical conductivity of the skin and cardiovascular signals.

Monitoring autonomic reactivity using comfortable, wireless, wearable packages could enable new *in situ* experimental paradigms and address some of the shortcomings associated with traditional methods of recording the ANS in persons with ASD. For instance, these sensors could enable longitudinal studies of individuals that yield data beyond the traditional "snapshot" timeframe, providing new insights on within-person, within-group, and across-group differences over time, and capturing phenomena of interest that are hard to replicate in laboratory settings, e.g., panic attacks. Measuring and communicating ANS patterns that precede, co-occur, and follow an event could also provide rich data enabling new ways to anticipate, respond to, and ultimately prevent problem behaviors (e.g., self-injury, aggression towards others).

Interactive Social-Emotional Toolkit (iSET)

Many first-hand accounts from people with ASD highlight the challenges of interacting

Figure 5. MIT Media Lab wearable EDA sensor. (Right) Sensor with disposable Ag/AgCl electrodes attached. (Left) Elastic strap with hardcase form factor that contains the sensor.



socially and difficulties inherent in the real-time processing of high-speed, complex, and unpredictable information like nonverbal cues (e.g., facial expressions) or making eye contact while processing language at the same time. Difficulties such as the following are also well-documented in a large body of empirical literature: 1. difficulty relating to other peoples' nonverbal cues and mental states (Baron-Cohen, 1995); 2. atypical eye-gaze processing (Klin *et al.,* 2002); 3. difficulty understanding and expressing one's own feelings (Hill *et al.,* 2004); and 4. trouble gauging the interests of others in conversation (Klin *et al.,* 2000). These challenges affect interaction partners as well, making it hard for family members and others to understand what the person is trying to communicate.

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Utilizing recent advances in pervasive and ubiquitous computing, sensors, and camera technology, it is now possible to have a range of on-body sensors that communicate to a portable device such as a mobile phone or ultra mobile PC. Building on these advances, we are developing an interactive social-emotional toolkit (iSET) (figure 4): a suite of wearable, wireless technologies that enable the capture, real-time analysis, and sharing of *in situ* social-emotional cues from faces, voices, and gestures of self and/or interaction partner(s). The technology components of iSET include a wearable camera that can be worn facing the wearer (Self-Cam) or facing outward (Head-Cam). The captured video is processed using real-time video-pattern analysis algorithms and is tagged at multiple granularities (facial actions, communicative facial/head gestures, and emotions) (el Kaliouby and Robinson, 2005).

The iSET project makes these wearable components available and accessible to individuals on the autism spectrum in the hope that it will allow this population to systemize, quantify, and reflect on their social interactions, which otherwise may seem confusing, overwhelming, and beyond their control. iSET is also designed to be fun, turning social interactions into a stimulating game that might motivate participants to engage in communication. The data and analyses offered by iSET also facilitate the sharing of social experiences with family members, teachers, and friends, and thus are inherently social.

Currently this system is being iteratively tested in the following scenarios at a large school for individuals with ASD:

Face and eye contact. "Head-Cam" or "Third-Eye" is a wearable camera that points outward and is aligned with the wearer's field of vision (Lee *et al.,* 2008). The video stream is input to face-detection software that quantifies how much face-contact happens in a natural conversation.

Systemizing social-emotional cues in self and others. Many individuals on the autism

Figure 6. *A* student on the autism spectrum using iSET with his teacher to capture, tag, and analyze facial expressions.

spectrum report difficulties expressing themselves in socially appropriate ways, and find it hard to identify their own feelings, as well as the feelings of others. "Self-Cam" is designed to help a person re-experience and reflect on how he/she appears to others (Teeters, 2007).

Learning what matters. While many interventions address the problem of recognition of social-emotional cues, very few teach individuals on the autism spectrum how to identify the cues to which it is most important to pay attention. Without this aspect of social processing, a person might attempt to process every single instance of social cues, an undoubtedly time-consuming and cognitive overloading process that detracts from that person's ability to respond in real time to his/her interaction partner. "Expressions Hunt" is a situated game we are developing in which individuals are given the task of eliciting and capturing various facial expressions such as smiles or frowns from others using a wearable camera. In this game, wearers have to think about eliciting, not just recognizing and capturing a state.

REDEFINING THE HUMAN CONDITION

We live in exciting times, as unprecedented progress in science and technology redefines human disability. Institutional collaboration and the integration of a broad range of disciplines are producing sophisticated solutions which allow people with once-debilitating physical and mental health conditions to lead healthy full lives. Meanwhile, novel technologies that create intimate connections between man and machine are augmenting human abilities beyond natural limits. Without a doubt, the contributions of leading scientists and engineers, including those at MIT's

Biomechatronics and Affective Computing Groups, are forcing society to reexamine disability and what it means to be human.

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