Conversations in BME

wearable technology for biomechanics: e-textile or micromechanical sensors?

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The possibility of gathering reliable information about movement characteristics during activities of daily living holds particular appeal for researchers. Data such as this could be used to analyze the performance of individuals undergoing rehabilitation and to provide vital information on whether or not there is an improvement during a neurorehabilitation protocol. Wearable devices are particularly promising toward this aim, because they can be used in unstructured environments (e.g., at home). Recently, two different approaches in this area have become very popular and show promising performance: the use of inertial sensors together with advanced algorithms (e.g., Kalman filters) and the development of e-textile, in which the sensing technology is directly embroidered into the garment worn by the user.

Prof. Peter Veltink from the University of Twente and Prof. Danilo De Rossi from the University of Pisa are pioneers in these two fields. Peter was among the early researchers who worked to combine different inertial sensors to extract joint kinematics, whereas Danilo developed one of the first e-textile sensing devices to be used in biomedical applications, primarily in functional assessment and rehabilitation. Peter and Danilo analyze the pros and cons of these two approaches to wearable technology in this conversation.

> Wearable micromachined sensors can be very powerful in providing an accurate biomechanical analysis under ambulatory conditions.

Peter Veltink: In recent years, wearable technology has been developed for biomechanical analysis under daily-life conditions [1]–[4]. This technology provides the possibility of investigating how individuals perform motor tasks during daily life and for longer periods of time, thus providing information not obtainable in the laboratory. Applications include not only monitoring and daily-life therapy in rehabilitation and neurology [5]–[7], ergonomics [8], and sports [9] but also in gaming and motion capturing for the animation film industry.

Danilo De Rossi: Yes, measuring and monitoring parameters related to human movement have indeed a wide range of applications. As of now, the standard motion analysis instruments are primarily stereophotogrammetric, magnetic, and electromechanical systems. These devices are very accurate, but they operate in a restricted area and/or require the application of obtrusive parts on the subject body. On the other hand, recent technological developments have led to the design and development of new tools in the field of motion classification and its quantitative assessment that are comfortable for the user, portable, and easily usable in unstructured environments. We know that human movement monitoring often needs to be associated with continuous and synchronous recording of various body signals such as vital signs and electromyographic (EMG) response. This is particularly needed in application fields such as sport and wellness as well as medical diagnostics and rehabilitation. Therefore, in these cases, the requirements of unobtrusiveness, comfort, and user acceptability are of paramount importance, and issues such as easy integration and the development of powerful portable acquisition and processing units is crucial. In addition, gesture and posture capture and classification systems are also becoming very important in the development of body–machine interfaces, presence, and social communication platforms.

Peter: Indeed, ambulatory assessment of human motor behavior during daily life can provide several kinds of relevant information. First, the motor task performed at any time can be identified. This is a classification problem. Second, the time at which motor tasks are performed can be determined. In combination, this process, often referred to as activity monitoring [10]–[13], is important for tracking daily-life activities. It can provide information on

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whether stroke patients become more active during daily life after a rehabilitation treatment. It can also be part of a personal coaching system for patients with chronic obstructive pulmonary disease to help them lead an active life within safe boundaries or of a wearable system to monitor heart patients during daily life by relating motor activities to cardiovascular assessment [14], [15]. Finally, ambulatory monitoring systems can provide information on how individuals perform motor tasks during daily life. Such an analysis can be limited to quantitative assessment of body movement [16] but may also require quantitative measurement of interaction forces with the environment, muscle activation (EMG) [17], and other sensory modalities related to motor control (Figure 1).

Danilo: That's true. Currently, most prototypes of wearable systems for these types of biomechanical analysis are based on micromechanical transducers (mainly accelerometers and gyroscopes) that are directly applied on the body segment to be monitored. Accelerometers are widely used for the automatic discrimination of physical activity and for the estimation of body segment inclination with respect to the absolute vertical. Body segment orientation can also be estimated by using the combination of different sensors through data fusion techniques [inertial measurement units (IMU)]. Usually, triaxial accelerometers (inclination), triaxial gyroscopes (angular velocity), magnetometers (heading angle), and temperature sensors (thermal drift compensation) are used together [18].

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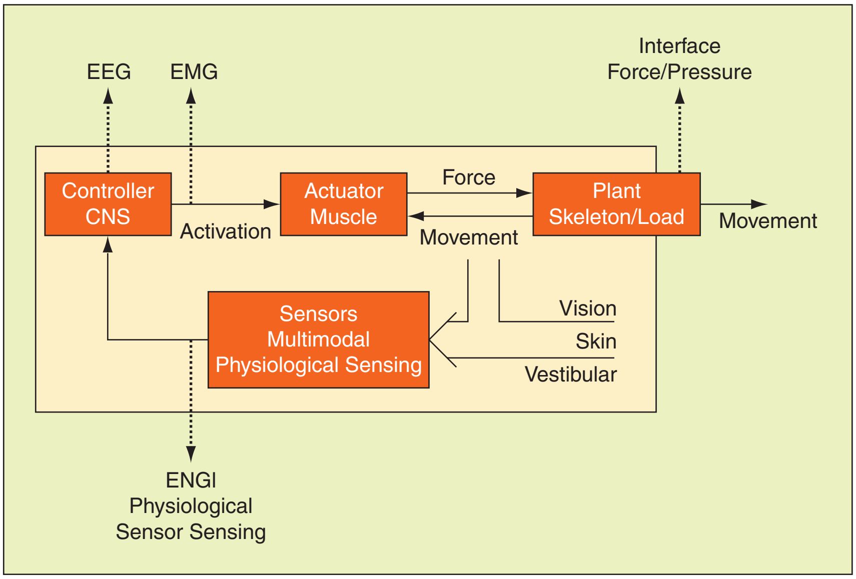

Fig. 1. To observe how individuals control their body movements in an ambulatory setting, several signals can be derived from the physiological motor control system, including neural signals from the central nervous system (e.g., electroencephalography), neural activation of the muscle (EMG), interaction forces, body movements, and neural signals from the physiological sensors.

I am sure that you, Peter, because of your pioneering and important work in this area, have much to say regarding the pros and cons of discrete, multifunctional, microelectromechanical sensing.

Peter: Thank you, Danilo. Over the past decades, micromachined inertial sensors have become available, and their performance and power requirements have been improved. Inertial sensors, accelerometers, and rate gyroscopes provide quantitative information about acceleration and angular velocity from which we can estimate orientation and change of position through adequate sensor fusion. The three-dimensional (3-D) accelerometers provide inclination information when they are not accelerated, and therefore, they only sense gravity. Alternatively, they provide information about acceleration if the gravity component of the sensed signals can be subtracted based on orientation information. This requires additional information from other sensory sources.

Danilo: I believe that the main advantages of using accelerometers in motion analysis are their very low encumbrance and the low cost. Limits are related to the possibility of obtaining only the inclination information in quasistatic situations since the effect of the system acceleration is a noise and the double integration of acceleration to estimate the segment absolute position is unreliable.

Peter: I agree that we can only obtain useful information concerning 3-D motions using inertial sensors if we are aware of their limitations. It has been demonstrated that 3-D orientation can be accurately estimated by fusing the information derived from accelerometers with the angular velocity information measured by rate gyroscopes [19], [20]. In addition, magnetometers may have to be used to avoid heading drift, but they are sensitive to magnetic disturbances [21], [22]. Orientation information is also required to represent 3-D acceleration derived from accelerometers in global coordinates, which allows estimation of velocity and position change by subsequent integration over time [23]–[25]. These estimates deteriorate over time because of integration drift. Therefore, velocity and position change can only be estimated over longer periods of time if additional position and velocity information is available at regular times. Such information can be derived from other sensory modalities or by applying additional knowledge of the movements performed or conditions under which they are performed. In this way, foot position and orientation can be tracked continuously during gait when zero velocity updates and information about orientation and vertical position during the stance phase are applied [24], [25].

Fig. 2. Experimental instrumented shoe with six degrees of freedom force and moment sensors under heel and forefoot coupled to inertial movement sensors (24).

Danilo: Indeed, IMU devices provide quite an accurate recording of body kinematics, but they are bulky and body fixing is cumbersome. In addition, they are susceptible to magnetic disturbances, are not reliable in the case of intense activities, and are still quite expensive (in order of the thousands of Euros for each body segment).

Peter: Although complete IMUs may be relatively bulky and costly, individual micromachined accelerometers or rate gyroscopes are small and relatively cheap.

In addition to the limitations of inertial sensors mentioned earlier, it should also be noted that they do not provide any information concerning relative positions on the body, which are, however, very important in kinematic and biomechanical analyses. These positions can be estimated using a kinematic model of the body, assuming certain segment lengths and joint characteristics or measured at regular times using additional sensing and actuation systems, like on-body magnetic actuation and sensing [18], [26]. Therefore, inertial sensors can provide accurate 3-D movement analysis of the human body, but this process has important limitations that can be resolved in many cases by using additional knowledge and additional sensory information.

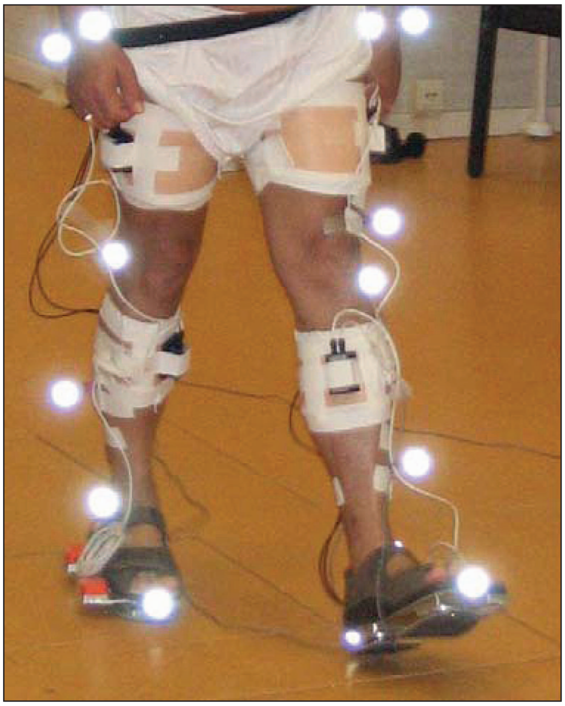

Fig. 3. Experimental evaluation of center of mass (CoM) analysis using instrumented shoes in a stroke subject. The movement sensor modules, additionally mounted on the legs, were not used in the CoM analysis. A conventional camera-based movement analysis system and force plates were used as a reference for evaluation. (Courtesy of Roessingh Research and Development, Enschede, The Netherlands.)

Therefore, ambulatory biomechanical analysis of motor task performance may require quantitative 3-D sensing of interaction forces with the environment in addition to quantitative movement analysis. We have demonstrated the potential of such an analysis by showing that shoes instrumented with 3-D movement and force sensing can provide adequate information about body balance during ambulation [24], [27], [28] (see Figures 2–4). Currently, we develop methods for quantitative analysis of dynamic interactions between the body and the environment, including estimation of power transfer and dynamics by relating movement and force at the interface [29].

Danilo: Now, we are also seeing an emerging concept in wearable technology related to electronic textiles. The idea of e-textiles, a viable solution for implementing truly wearable, smart platforms as bidirectional interfaces with the human body and functions, has emerged due to the work of independent groups almost ten years ago and today is actively explored in the health domain [30]. Textiles, being a pervasive and comfortable interface, are an ideal substrate for integrating miniaturized electronic components or even, through a seamless integration of electroactive fibers and yarns, have the ideal possibility to become fully functional electronic microsystems [31].

For example, knitted integrated sensors in a shirt, which comprises an electronic unit for signal processing and telecommunication, have been realized for cardiopulmonary secondary prevention [32]. Fabric electrodes and piezoresistive sensors have been capable of providing continuous recording of electrocardiogram, EMG respiratory activity, and limbs actigraphy, thus combining simultaneous acquisition of physiological and biomechanical variables [33]. Multiaxis human joint angle measurements have been attempted using wearable piezoresistive fibers properly fixed to the lower limbs [34].

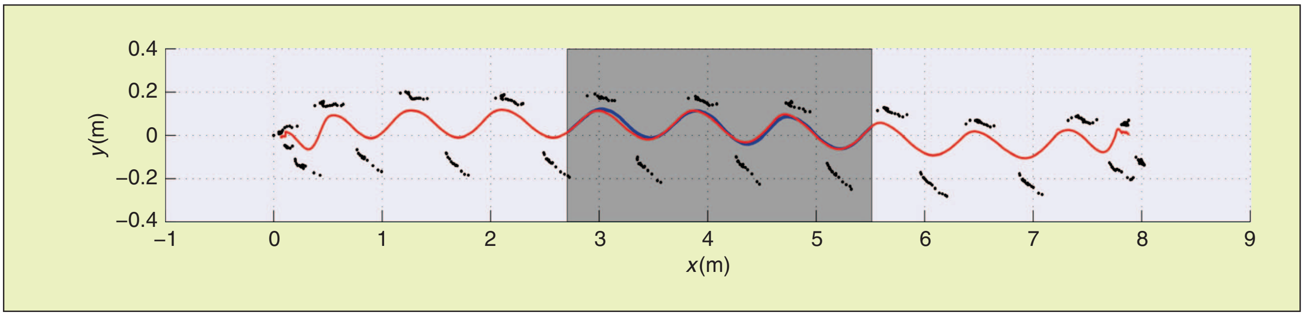

Fig. 4. Example result of foot placement and CoM trajectory estimate derived from instrumented shoes (27). The gray area indicates the measurement space of the camera system; the red and blue lines are the CoM trajectory estimates by the instrumented shoe and the reference camera system, respectively. In contrast to the reference system, the instrumented shoes can track foot placement and CoM continuously. The results indicated that the stroke subject is leaning toward his healthy side.

Peter: As you explain, electronic textiles do indeed provide a very promising integration platform for many kinds of complementary sensing modalities. This truly distributed sensing platform has the potential to provide very complementary features to micromachined sensing systems.

Danilo: That's true. Recently, we have even seen developments in an innovative methodology exploiting redundant fabric-based sensor arrays with the intent of reconstructing body gesture and posture [35]. Piezoresistive rubber sensors have been screen printed onto an elastic fabric substrate with no changes in the mechanical and thermal properties of the fabric, thus maintaining the user comfort unaltered during operation (see Figure 5 for an example of application in the field of neurorehabilitation).

The basic concept of the proposed technology is that having a redundant distribution of sensors around the joints to be monitored provides possibilities to associate the sensor status (the set of the actual sensor values) to parameters related to user movements through proper identification procedures. Several prototypes have been realized using this technology to monitor body posture and gesture in rehabilitation and human–machine interaction for disabled people [36] (see Figures 6 and 7).

Fig. 5. A subject wearing a fabric-based upper-limb monitoring device developed for poststroke telerehabilitation is shown. The system drives a kinesthetic avatar on the laptop screen. Black stripes are both screen printed piezoresistive rubber sensors and sensors tracks (36). (Courtesy of the University of Pisa.)

Peter: Wearable micromachined sensors, possibly combined with other sensing and actuation modalities and adequate supplementary knowledge, can be very powerful in providing an accurate biomechanical analysis under ambulatory conditions. However, we need to be aware of the limitations of this approach. Alternative approaches such as distributed sensing in textile, which is Danilo's expertise [2], [12], [35], can be good alternatives or may be preferable in many situations. Although such sensor systems may not provide direct and accurate measurement of required physical quantities such as orientation, relative position, and pressure or force, these quantities may be estimated after adequate calibration by combining the redundant information from all sensors [37]. In addition, this approach may provide cheap and unobtrusive sensing, which is not always provided by the current generation of on-body inertial movement sensor systems. Such systems, which typically include 3-D accelerometers, angular velocity sensors, and magnetometers, as well as on-board processing, are often still relatively bulky, although micromachined accelerometers and rate gyroscopes are, by virtue of their design, very small and capacitive accelerometers have, in addition, very low-power requirements. This even makes them suitable for implanted applications, such as activity-dependent cardiac pacing. In contrast to small inertial sensors, no adequate 3-D micromachined force sensors are currently available [38], which limits the application of wearable systems for biomechanical analysis. However, there is no principle reason why such sensors cannot be developed. In current projects, we collaborate with micromachining experts who do so.

Danilo: We have found that real-time 3-D reconstruction of body kinematics has been hard to obtain with e-textile systems since their conformability to body structure inevitably leads to a strong dependence of the system performance from garment fitting. That is, skin stretching (as well as the fabric) corresponding to different areas of a joint differs from one subject to another, and so using strain sensors adherent to skin has to be personalized according to the subject anthropometry. This problem has been taken into account by considering the human kinematic chain as a part of the system. By using identification algorithms, functions that relate joint angles to electrical values presented by the sensor network have been created. The construction of these functions is quite complex, and the time of computation dramatically increases with the number of degrees of freedom (DoF) and with the accuracy required to the system to be resolved. To increase the accuracy and reduce computational complexity of inverse kinematics, textile-based electrogoniometers have been designed and used [39] in combination with surface stretch sensor arrays.

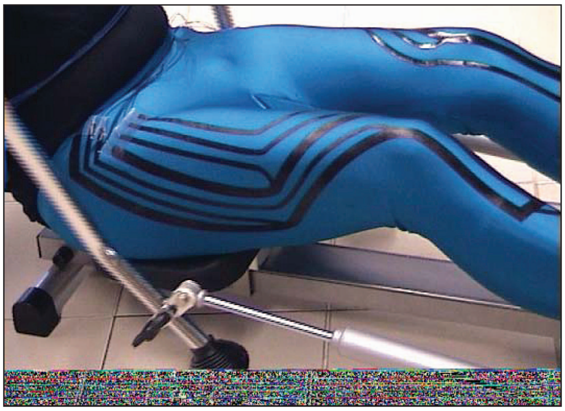
Fig. 6. A prototype of fabric-based motion classification garments based on redundant sensors array is shown for monitoring leg kinematics during rowing (41). (Courtesy of the University of Pisa.)

Peter: The sensor approach you describe, using redundant sets of sensors with hysteresis and long relaxation times, reminds me of a study of Haugland et al. [40]. He tried to relate indentation of and pressure on the paw of a cat to the electroneurogram (ENG) signal that is derived from the cat's tibial nerve, which showed very similar sensor characteristics as your published research. Haugland et al. were able to construct and identify a model to predict the measured ENG from known skin indentation and pressure, but this model could not be inverted because of the nonlinear characteristics, such as hysteresis and relaxation. Apparently, our body has to observe its state using signals from sensors that have such nonlinear characteristics that the sensed state may not be uniquely determined at any time. Still, our body is able to operate adequately under this condition by fusing sensory information from several sources and using context and history information. In addition, Haugland et al. were able to use the described ENG signal to control functional electrical stimulation (FES) supported hand and arm functions in paraplegics and hemiplegics. In fact, not only the sensors described in your research but also the inertial sensors exhibit important similarities to the sensory modalities of our body. They have similar characteristics as the human vestibular organs, which are important in balance control and sense of orientation. Although the sensed quantities can be uniquely estimated from the signals they produce, most of the quantities of interest, (acceleration, velocity, position change, and orientation), can only be estimated by fusing complementary information. This is true for artificial as well as our physiological inertial sensors.


Fig. 7. A prototype of fabric-based motion classification garments based on redundant sensors arrays is shown monitoring torso and neck movement as a human–machine interface for wheelchair control (42). (Courtesy of the University of Pisa.)

Danilo: I fully agree with this analysis. In biological systems, the intrinsic noisy, sloppy, and poorly selective transduction characteristics of individual mechanoreceptors are compensated by redundant allocation, powerful peripheral processing, and effective and continuous recalibration through supervised and unsupervised learning and training. A truly bioinspired sensing system should have these features to some extent, not just as a purely mimicking exercise but as a result of solid engineering reasoning. All this is particularly true in wearable systems adherent to soft tissues in multi-DoF kinematic chains.

Peter: There is an additional point I want to address. In human motor control and biomechanics, it is often more or equally important to estimate changes of sensed quantities than their absolute values. Adequate balancing of our body requires a good estimate of velocity in addition to position or orientation, as can be learned when studying balancing of an inverted pendulum. In control of hand grip, slip detection is important in addition to estimation of grip force. For this reason, body sensors are often very sensitive to changes. This is also apparent in the characteristics of printed textile sensors that you described. By virtue of their sensing principle, inertial sensors even have predominantly derivative characteristics.

In biomechanical analysis, estimation of derivatives of positions and orientations are also often required, for example, when estimating forces that accelerate masses. Although the traditional lab-bound movement analysis systems measure positions very accurately, their accuracy in estimating velocities and accelerations is often limited. In this respect, many of the wearable sensing modalities have superior characteristics.

Danilo: It is in fact well known that our senses and, I would say, also our psychological attitude are responding to changing of events more than to steady signals and inputs. In wearable systems too, base line suppression might be a necessity, since drift is unavoidable and frequent recalibration is unacceptable.

Peter: Finally, I agree with you that wearable textiles, including printed sensors and embroidered material with small accelerometers and force sensors, may provide very valuable future possibilities not yet explored. This combination of sensors is especially interesting for nonrigid body segments, such as the trunk, feet, and hands. The form of and relative positions on such segments may only be estimated from the signals of distributed inertial sensors, spatially sampling the segment, when using assumptions or a compliance model of the segment, while it may follow relatively naturally from flexible printed sensors. Relative positions may be estimated more accurately, when using additional magnetic actuation and sensing [26], with coils and micromagnetic sensors integrated in the textiles. The combination of these modalities may yield a continuous representation of form and provide accurate information about positions, derivatives of positions, and position-dependent stress at the interface with the environment for any point of the segment, not otherwise obtainable. The printed e-textile may also be important in providing a mechanically adequate embedding of the microsensors and wiring of the matrix of sensors for powering and transmission of the sensor signals. It may be essential in developing instrumented shoes [24] for biomechanical analysis that are not distinguishable from normal shoes, instrumented gloves that provide full information about the dynamic interaction with the environment [29], and adequate analysis of the movement and loading of the trunk during physical work [17].

Danilo: It is also my opinion that future developments in the field of wearable motion capture systems must rely on synergistic integration of micromechanical and textile sensors with appropriate data fusion algorithms to overcome the limits of currently available systems.

Accelerometers are widely used for the automatic discrimination of physical activity and for the estimation of body segment inclination with respect to the absolute vertical.

To conclude, I want to stress that fully wearable, accurate, autonomous, and user-friendly systems are still not available, but they are now foreseeable in a not too distant future. On the e-textile side, a very recent field of investigation, much more work needs to be performed, either at the level of technology development or at the level of algorithm development for inverse kinematics. The proper allocation of textile sensors arrays [12] is also an issue to be further addressed for more accurate and computationally efficient reconstruction of limbs positions when it is to be performed in real time. Integrating micromechanical with e-textile sensors has never been attempted to date; this synergistic approach has to be investigated, and appropriate sensory fusion methods and algorithms have to be implemented.

Danilo De Rossi received the laurea degree in chemical engineering from the University of Genoa in 1976. From 1976 to 1981, he was a researcher at the Institute of Clinical Physiology, Italian National Research Council (CNR). He is a full-time professor of bioengineering at the Faculty of Engineering, University of Pisa. His scientific activities are related to the study of transduction properties of organic and polymeric materials and to the design of sensors and actuators for bioengineering and robotics. More recently, he has been focusing on e-textile and wearable systems for health. He received the Bioengineering Forum Award of the Biological Engineering Society, United Kingdom, in 1980 and the Young Investigator Award of the American Society for Artificial Organs, United States, in 1985. He has been the founding editor of the journal *Material Science and Engineering C*, and he is a member of the editorial board and a reviewer for several scientific journals. He is the coauthor of more than 150 peer-reviewed papers in international science journals, more than 200 peer-reviewed proceedings and book chapters, and eight books. He is also a coinventor of 14 patents.

Peter H. Veltink received his M.Sc./laude degree in electrical engineering in 1984 and his Ph.D. degree in electrical nerve stimulation in 1988 at the University of Twente. Currently, he is a professor of technology for the restoration of human function and chair of the Biomedical Signals and Systems Department, University of Twente. His research areas include biomechatronics, artificial motor control, ambulatory sensing of human motor control, specifically ambulatory movement and force sensing, with applications in rehabilitation medicine and biomechanics and neural engineering: neurostimulation for neuromodulation, including deep brain stimulation, neurocardiology, as well as stimulation of spinal cord and cortex for suppression of pain. He is an associate editor for *IEEE Transactions of Neural Systems and Rehabilitation Engineering* and a reviewer for many scientific journals. He is the coauthor of 95 peer-reviewed journal papers and many peer-reviewed conference papers. He was the treasurer of the International FES Society from 1996 to 2001 and has been the chair of the Benelux IEEE Engineering in Medicine and Biology Society chapter since 2005. He received the Royal Shell Stimulating Prize in 1997 for his contribution to the rehabilitation-engineering field.

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