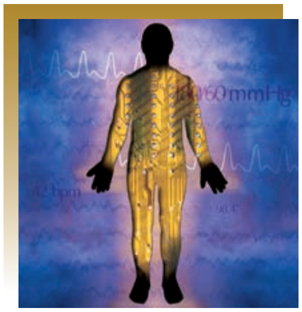

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Dynamically Responsive Intervention for Tremor Suppression

The DRIFTS Project Aims to Create Wearable Active Orthoses That Suppress Upper-Limb Tremor While Allowing Natural Movement

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Tremor is characterized by involuntary oscillations of a part of the body. The most accepted definition is as follows: "an involuntary, approximately rhythmic, and roughly sinusoidal movement" [1]. Tremor is the most common movement disorder and is a major source of functional disability, affecting many of the daily living tasks. Although the most common types of tremor have been investigated for more than a century, many questions remain open in terms of pathophysiology and treatment options [1]-[3]. Despite outstanding advances in the understanding of drugs actions and in the surgical techniques, the tremor cannot be fully or sufficiently controlled in about 40 to 50% of patients.

In this article we present an overview of a multidisciplinary project whose acronym is DRIFTS (Dynamically Responsive Intervention For Tremor Suppression). This project is financially supported by the European Commission's Fifth Framework Programme and aims to create proof-of-concept prototypes of wearable active orthoses for the suppression of upper limb tremor while preserving natural movement. Another major goal of the project is the development of a prototyping and evaluation platform for the future elaboration of wearable ambulatory tremor suppression devices. The prototyping platform will be used to assess the efficacy of available sensing, actuating, and control technologies for tremor suppression.

Tremor: Clinical Aspects

Clinically, several forms of tremor can be distinguished [1]-[3]. The most common classification is by position/motor behavior. According to this classification, there are four categories of tremor: rest, postural, kinetic, task-specific. For the sake of clarity, we will not go into the details of hysterical tremor, a fifth category, in this article.

Rest tremor is typically observed in Parkinson's disease [1]. Tremor occurs when the affected part of the body is in repose and fully supported against gravity, requiring no voluntary contraction. Typically, the tremor disappears with the onset of movement. *Postural tremor* occurs when the subject attempts to maintain a posture, such as maintaining the upper limbs outstretched. The following conditions are associated with postural tremor: physiological tremor, essential tremor, cerebellar tremor, post-traumatic tremor, peripheral neuropathy. *Kinetic tremor* occurs during purposeful movement; for example, during finger-to-nose test (the patient is asked to put the index finger on the nose). Kinetic tremor is highly suggestive of a cerebellar disorder (cerebellar ataxia) or a disease involving cerebellar pathways. Midbrain tremor combines rest, postural, and kinetic tremor. *Task-specific tremor* appears when performing goal-oriented tasks such as handwriting, speaking, or standing. This group consists of primary writing tremor, vocal tremor, and orthostatic tremor. Task-specific tremor can be viewed as a form of kinetic tremor that appears during specific tasks.

The Target User Group

The target user group of the current project consists of individuals suffering from rest, postural, and/or kinetic tremor.

Parkinson's Disease

Parkinson disease is a slowly progressive degenerative disorder of the central nervous system, initially reported by James Parkinson in 1817. Clinically, the patient exhibits a rest tremor, rigidity, akinesia, and postural reflexes impairment.

Parkinsonism can be classified into three general etiologic groups [2]; namely, idiopathic, secondary or acquired, and "Parkinson plus." Among them, the idiopathic Parkinson is the most common form of the disease. It affects 0.8 to 1% of the population over the age of 50 in the United States, with an estimated incidence of 40,000 new cases per year [2]. The general agreement is that both males and females seem to be affected equally, although some studies have revealed a male preponderance. Parkinson disease ranks behind cerebrovascular diseases and arthritis as the third most common chronic disease of the late adulthood groups [2]. The incidence increases with age, with the peak onset between the sixth and eight decades.

The rest tremor remains the most readily identifiable sign of Parkinson's disease [1]. In up to 75% of the patients, it is the first motor sign, beginning usually unilaterally and distally in the upper limb. The "pill-rolling" tremor affecting fingers and associated with a pro-supination motion is typical, with a frequency ranging from 3.5 to 6 Hz and an asynchronous pattern on electromyographic recordings. The tremor will

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The DRIFTS approach to the reduction of tremor is based on a wearable concept in which tremor energy is selectively damped out by either passive or active means.

usually spread proximally. Tremor disappears during sleep and worsens with stress (this is a general rule for the majority of tremors). The tremor in Parkinson's disease is likely centrally generated. The current hypothesis is that rhythmic activities are generated within basal ganglia, hence the effects observed during surgical deep brain stimulation.

Essential Tremor

This is the most common form of pathological tremor. Essential tremor is a postural and kinetic tremor that affects the upper limbs and the head. A resting component is present only rarely and typically occurs in the most advanced cases. An adduction-abduction movement of the fingers and a flexion-extension movement of the hand is typical; less often, a pronation-supination movement is seen. Essential tremor appears usually after the fourth decade. Some authors [2] report that familial tremor is said to be inherited at least in 50% of the cases. Essential tremor is slowly progressive.

Tremor frequency varies from 4.5 to 8 Hz. Frequency declines and amplitude increases with age. When severe it can be disabling and result in difficulty in writing and in handling tools. Up to 25% of the patients with this condition retire or change jobs as a result of tremor.

A prevalence of 500 to 1,000 per 100,000 for people older than 40 years is found in the literature [1]. The prevalence increases with age for both sexes and is slightly higher in men. It should be pointed out that only a small percentage of individuals with mild to moderate essential tremor comes to medical attention. Essential tremor is likely due to an overactivity of a generator located in posterior fossa (brainstem - cerebellum) and interacting with thalamo-cortical pathways.

Kinetic Tremor

The most common type of cerebellar tremor is kinetic. It is a disabling jerky, arrhythmic interruption of the normal progression of voluntary movement, becoming more pronounced as greater precision is demanded. It can be seen by having the patient do a finger-to-nose test or a heel-to-knee test [1]. The frequency of the tremor varies from 3 to 5 Hz. Kinetic tremor is observed in cerebellar ataxias (sporadic and hereditary), in essential tremor, in multiple sclerosis, following a brain trauma, and in midbrain tremor.

There is no drug that is active to treat kinetic tremor and surgery is disappointing. The added inertia of wrist weights attenuates cerebellar tremor and is useful in some patients [4]. Kotovsky et al. [5], however, identify both essential tremor and cerebellar tremor as the most indicated targets for an active orthosis, arguing that essential tremor would account for 2/3 to 3/4 of the total estimated market. The figures of potential users are roughly estimated between 160,000 and 1 million people in the United States. Some other authors support these figures and report that about 160,000 people have kinetic tremor in a distal upper limb of sufficient severity to warrant use of a tremor-suppression orthosis.

Approach in the Study of Tremor

Until now it has been difficult to provide a specific definition of a possible goal in tremor suppression. Several goals can be considered, ranging from improvement of the client's quality of life to the specification of the level of reduction in involuntary tremor-induced movements.

Since one primary aim of the DRIFTS project is the development of an experimental platform and the validation of the usability of this platform through the evaluation of one or more concepts, specific goals will not be determined until later in the project. Preliminary studies will provide data that will help us define and specify the ultimate goals of the project.

To illustrate that there are various end goals we could strive for and that tremor suppression alone is not sufficiently specific, several options are listed below:

- suppression of the tremor in the joints as such (amplitudes and frequencies for the separate joints)
- minimize energy consumption of the human limb
- subjective experience of a reduction in tremor
- increase of functionality of the total arm-shoulder system where those elements of the tremor are suppressed, and those activities that are judged to be most important, can be performed in a more efficient way
- decrease of the movement patterns in such a way that the aesthetic aspect of the tremor, the movement pattern, is improved
- a combination of the above and other possible goals and suppress and improve what you can achieve: just "go-for-it."

Biomechanics of Upper Limb Movements

There are two main concerns regarding biomechanics and tremor:

- tremor characterization
- loads and/or forces needed to counteract tremor

Tremor Characterization

There are many studies addressing the measurement of tremor at the distal part of the arm, since the tremor is more disabling and visible at this level. Often these studies do not measure the contribution of each joint to the observed tremor. In the DRIFTS project, we aim to measure the contribution of each joint to global tremor. With wearable devices tremor can only be suppressed at the same level where it is produced (i.e., joint level). Tremor can be present or absent in any of the joint movements depending on the pathology and individual circumstances. Tremors involving pronation-supination of the forearm and flexion-extension of the wrist are especially important. In addition, proximal components of tremor can be very disabling due to their transmission along the kinesiological chain of the arm.

In order to assess tremor from a kinesiological viewpoint we have planned an experimental phase involving 30 patients. We have currently measured tremor in 12 persons, taking into account different kinds of tremor.

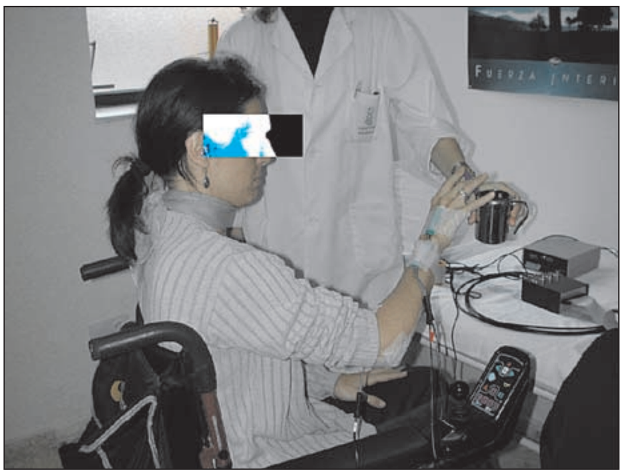

Fig. 1. Measurement session in which two goniometers can be seen: one for wrist movement, the other for prono-suppination.

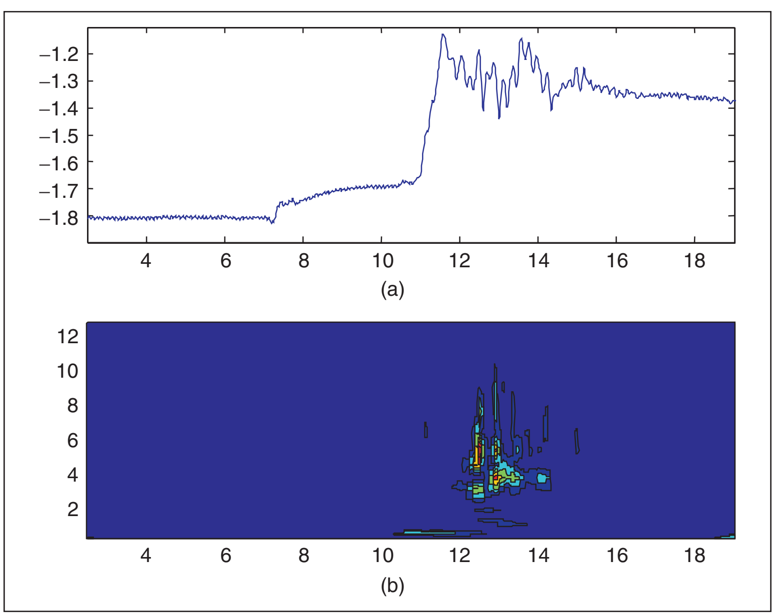

Fig. 2. Kinematic analysis of tremor during a finger-to-nose movement. (a) Wrist flexion-extension angle versus time. (b) Periodogram (frequency versus time) of the wrist flexion-extension angle.

Methods

Appropriate instrumentation has been chosen in order to comply with two main aspects:

- possibility to analyze the contribution of each joint to the final tremor
- ease of integration in the final prototyping platform.

Taking into account these aspects, extensometric electrogoniometers have been selected to measure the following movements (Figure 1):

- wrist flexion-extension
- wrist ulnar and radial deviation
- elbow flexion-extension.

An extensometric electrotorsiometer has also been included in order to measure forearm pronation-supination.

Results

Different kinds of tremor can be present:

- rest tremor
- postural tremor
- kinetic tremor: both in relationship with movements or with an increase of amplitude near the target.

However, tremor is not permanent. Therefore, it is very important to identify the onsets and offsets of tremor. Another important issue is to isolate the tremor component of movement, by distinguishing voluntary movement from tremor. Then we will be able to estimate tremor power at different levels (joints) and, also, the necessary joint moments of force required for compensation.

Frequency analysis has been applied to analyze kinetic tremor. Wavelets have been identified as a very useful tool to identify tremor onsets and offsets and the frequencies at which tremor occurs. Figure 2 shows a wavelet analysis of a finger-to-nose movement in a patient with cerebellar tremor. The lower part of the figure shows tremor frequency content versus time. The onset of tremor can be easily found at time = 12 s, when the finger is very close to the nose tip (target of movement). Also, frequencies between 4-8 Hz are clearly visible. These techniques can be very useful to perform objective measurements of any kind of tremor and can therefore be used to perform tremor functional assessment.

Loads Needed to Counteract Tremor

Pressure Sensitivity

Excessive pressure is one of the main concerns related to the application of loads to the body. There are several factors in relation with pressure that have to be taken into account:

- safety
- pain
- comfort.

Strategies to avoid safety problems and pain always try to distribute the load over a wide area in order to minimize the maximum pressure. Different skin receptors are involved in pressure and touch sensitivity. Some of them are specialized in touch, some others in pressure, and, finally, there are specific receptors specialized in vibrations (Pacini's corpuscles).

The response spectrum of those vibration receptors are distant (>60 Hz) from the frequencies involved in tremor (4-20 Hz); therefore, these kinds of receptors have been left out of our study.

Pressure and touch receptors are basically displacement sensors; thus, they are sensitive to skin deformation. Touch receptors are located close to the skin surface and are present in touch-specialized parts of the body such as hands, fingers, lips, etc.

Pressure receptors are located deeper in the skin structure. They are found all over the body, but density of receptors varies from one part of the body to another.

Methods

Pressure discomfort threshold has been studied in nine subjects, all of them affected by tremor at the upper limb. Measurement points have been located taking into account the common placement of load transmission elements of upper-limb tremor suppression orthoses. These points were chosen on the dorsal and palmar side, over muscles and over bony areas in order to have a good representation of the different areas of the forearm. We used a dynamometer for measurements (Figure 4). The indentor was an aluminum cylindrical cap with a contact flat surface of 1.3 cm^2 adapted to the dynamometer. The dynamometer was connected to a computer by means of a data acquisition card. Pressure was applied five times on each point. The sequence of pressure application was randomized previously, to avoid the learning effect of the patient in each point.

Results

Our study with patients revealed no significant differences in pressure sensitivity at different locations over the forearm. Differences between subjects have been identified.

Many factors affect the perceived sensation when load is applied to the skin:

- contact area
- pressure
- amount of load
- time of application (duration).

A feasible model to understand the way these parameters are involved in pressure perception can be seen in Figure 5.

Two different channels of sensitivity were identified:

- A fast reaction channel depending on maximum pressure (in our simplified model we considered the load equally spread along the contact area).
- A slow reaction channel depending on the load applied. This channel takes into consideration the so-called spatial summation theory. The total number of excited receptors can change a perceived sensation into discomfort or pain along time. This channel also performs an integration of the overall sensation along time, reducing the perceived sensation of discomfort of maintained or repetitive loads.

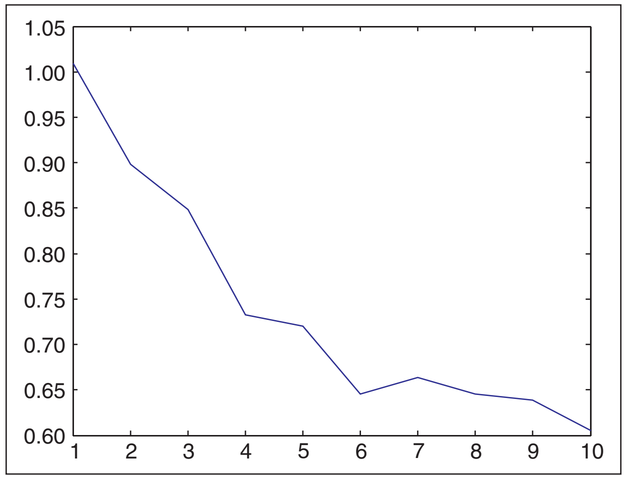

Fig. 3. Lowering effect of pain threshold through repetitive loads.

Fig. 4. Pressure sensitivity measurements.

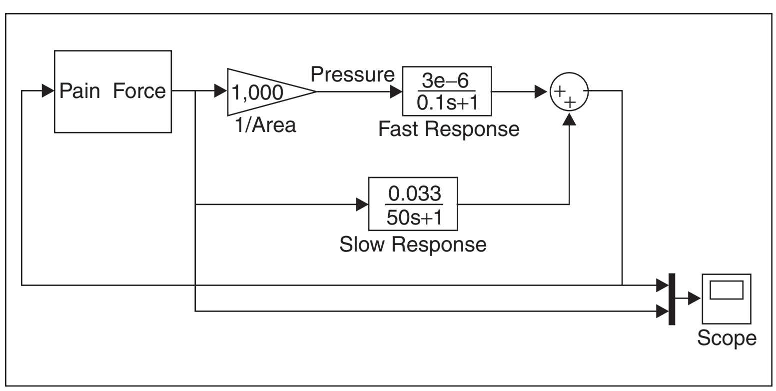

Fig. 5. Feasible model for sensitivity.

Control Technologies

The overall management is directed toward keeping the patient functioning independently as long as possible while minimizing disability. We have focused our work in assisting the limb with compensatory technology. Significant results have been obtained by other researches in reducing hand tremor by applying mass, fric-

The main challenge in this approach is to distinguish error from intended motion before error canceling can occur. This requires real-time error estimation.

tion, and viscous resistive forces. This can be approached in two ways:

- ➤ isolate the task from the tremorous limb in a frequency-selective manner
- ➤ decrease the amplitude of tremor.

The DRIFTS approach to the reduction of tremor is based on a wearable concept in which tremor energy is selectively damped out by either passive or active means. Several control strategies will be assessed as valid tools for technology-driven tremor management. In general, the candidate tremor suppression strategies will be based on:

- ➤ tremor data measurement with different sensor systems
- ➤ tremor motion discrimination from voluntary motion, through RT tracking or filtering algorithms
- ➤ application of inertial and damping loads, or their combination, as tremor reduction strategies
- ➤ application of active cancellation through the use of out-of-phase motion commands
- ➤ application of tremor reduction load through appropriate actuators.

Various preliminary steps are required for the effective implementation of these tremor suppression strategies:

- ➤ In-depth modeling of the biomechanical system: establishing the relationship between electromyography (EMG) and tremor kinetic data. Some techniques are based on cross-spectral methods to investigate the relation between simultaneously recorded; i.e., muscle activity (EMG) and acceleration or between position and EMGs.
- ➤ Analysis of the tremor time series. This analysis of the kinematics series is important because it allows us to better define the sensors that will be used. It addition, it will provide information on:
  - involved joints in tremor patterns
  - frequency and amplitude ranges
  - EMG pattern
  - effect of joint blocking on proximal and contra-lateral joints
  - classification of tremor signal: stationary, frequency drift…
- ➤ Estimation of tremor torque and energy.

The Wearable Orthosis for Tremor Assessment and Suppression (WOTAS) concept developed in the DRIFTS project will provide a means of testing nongrounded tremor reduction strategies.

As mentioned earlier, tremor force, position, velocity, and acceleration are required in order to set up and test all different control strategies. We first evaluate and analyze all the candidate sensors and actuators. We have restricted our analy-

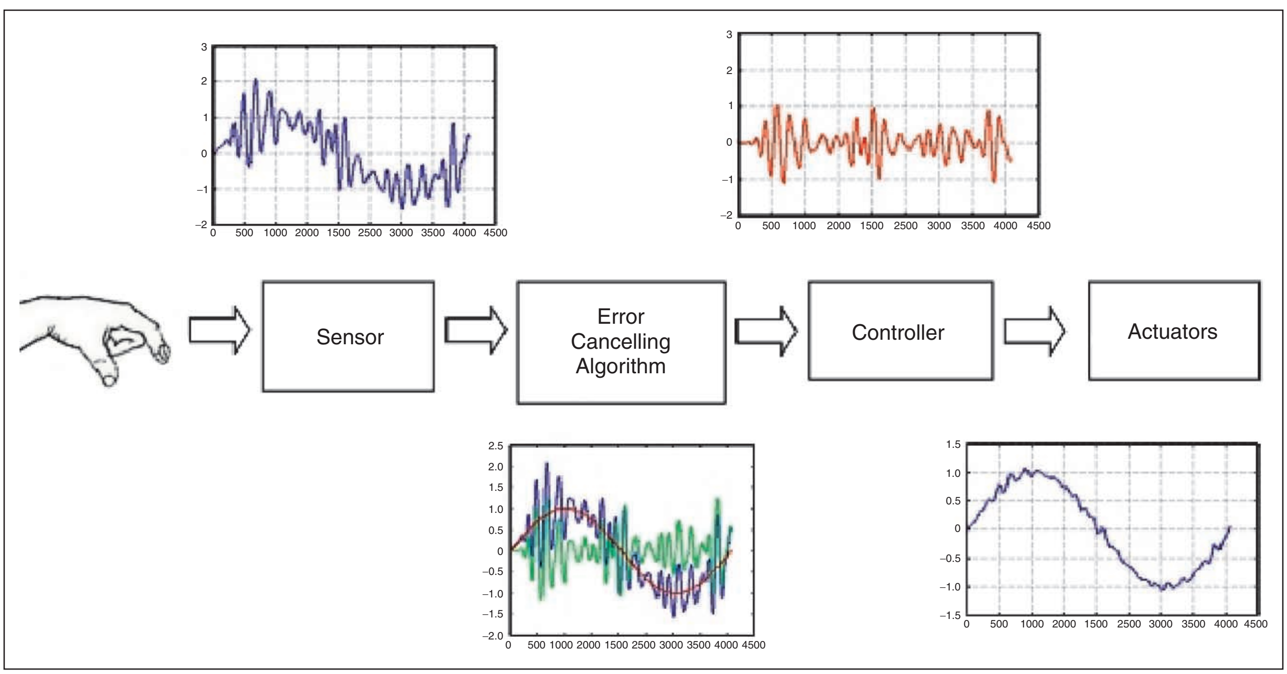

Fig. 6. Error compensating system.

The need to develop a suitable fluid to be used in a controllable passive actuator-based orthosis has led to the development and characterization of several fluid recipes.

sis to the following sensors: gyroscopes, accelerometers, and force sensors.

Following the previous analysis, gyroscopes have been selected as a promising technology. An analysis of commercial solid-state gyros has been performed and we have decided to use the GYROSTAR ENC-03J. Since these gyroscopes are applied to image stabilization in video cameras, it is expected to be a good alternative for tremor velocity measurement. In Figure 7, its main operational characteristics are summarized. A similar analysis has been performed for candidate accelerometers. Even when in the previous analysis the accelerometers were ranked third, a direct measure of acceleration is very interesting when attempting inertial loading control strategies.

A final version of the gyroscopes is shown in Figure 7. This version of the gyroscopes measures absolute angular velocity; thus, two of them are required to get the tremor contribution of each joint; we have one- and two-axis versions of the gyroscopes. Both versions incorporate an on/off switch, bandpass filtering (0.3 to 25 Hz), and batteries; therefore, no external energy source is required (sensors can be used for 10 h. per battery charge) and sensor gain can be adapted to render 1.5 V at maximum angular velocity (300 deg/s).

We have also decided to use force sensors in WOTAS. According to the analysis performed, we specified the following strain gage as force sensor. The selected strain gauge is the RS strain gauge and fits adequately with WOTAS requirements. To interface the strain gauges with the WOTAS electronic architecture, we have decided to use a strain gauge amplifier.

Control Architecture

The control architecture defined for a DRIFTS platform is based on a standard desktop to execute the orthosis control algorithm, electronic circuits to interface the sensor and the actuators with the computer, an orthosis structure, and a power supply connected to the orthosis actuators (see Figure 8).

We have decided to design the structural support of the orthosis in order to have a structure as close as possible to WOTAS requirements. The structural support we have designed is monocenter and its joint is designed in such a way that is easy to couple an actuator (Figure 9).

The two control strategies considered for this application are:

- changing biomechanical characteristics of the affected limb
- active isolation of the limb affected by the tremor.

We have focused our efforts in control strategies based on changing biomechanical characteristics of the tremorous limb through impedance control. Position, velocity, acceleration, and force are being examined to be feedback in such a way that we can perform the alteration of inertial properties of the limb; we can also apply viscous loading to the movement, or the combination of both (changing inertial properties and applying viscous loading to the movement). The basic scheme of the control architecture is illustrated in Figure 10.

In the control approach suggested to tremor suppression through impedance control, there are two feedback loops. The first one is responsible for tremor cancellation. In this loop we feed back information about tremor; in other words, the data are treated in order to only feed back information regarding the tremorous motion. The feedback coefficients a_1, a_2, and a_3 impact the effective mass, damping, and stiffness of the closed-loop system in an additive fashion.

The function of the other loop is that the orthosis offers the minimum resistance to the voluntary motion. The data are treated and we just feed back information regarding the voluntary motion, in such a way that with this loop we update the actuator with information related with voluntary motion. With

Fig. 7. Gyroscope.

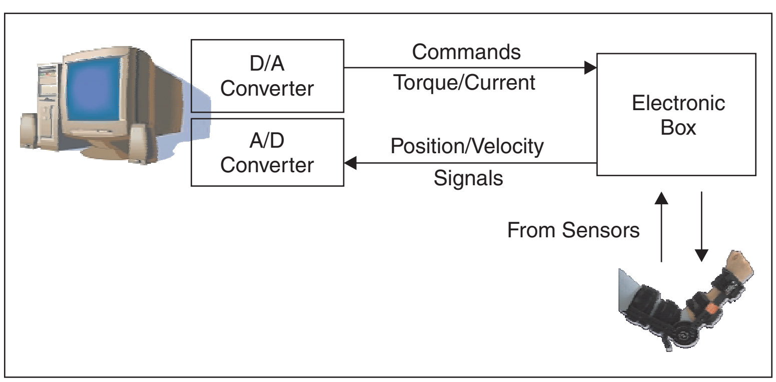

Fig. 8. DRIFTS platform control architecture.

this loop we intend to minimize elastic stiffness of the orthosis.

The main challenge in this approach is to distinguish error from intended motion before error canceling can occur. This requires real-time error estimation. There have been studies in recent years on the use of signal filtering for tremor attenuation, primarily dealing with pathological tremor.

Estimation techniques have been developed for tremor suppression. The most-used algorithm to estimate tremor is the weighted-frequency Fourier linear combiner (WFLC). The WFLC is an adaptive algorithm that estimates tremor using a sinusoidal model, estimating its time-varying frequency, amplitude, and phase. It is used by Riviere et al. [6] to develop an adaptive filter to cancel physiological tremor during surgery. Riviere is also investigating the application of neural networks to augment manual precision by canceling involuntary motion [7], [8], using the cascade learning architecture in order to estimate the undesired motion because of its versatility in learning unknown dynamics. Riley and Rosen [9], among others, have investigated lowpass filtering. Gonzalez et al. [10] proposed an equalizer to suppress pathological tremor.

Mechanisms

External mechanical devices have been developed over the years following two distinctive approaches: active or passive compensation based on grounded or wearable orthosis.

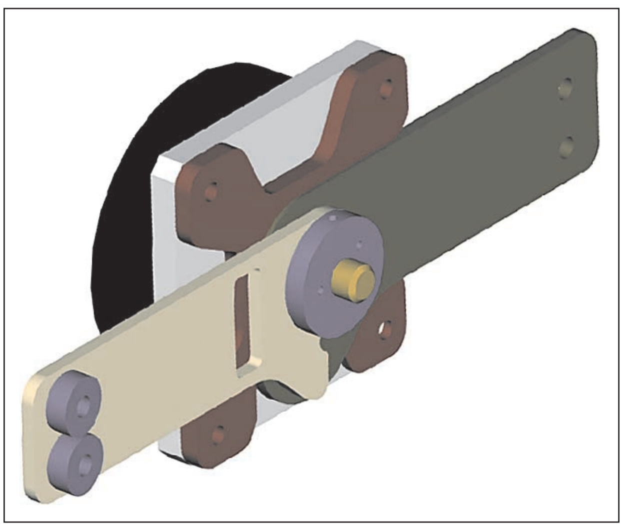

Fig. 9. DRIFTS platform orthosis structure design

Grounded devices have been developed to assist in ADL, such as eating or controlling an electrical wheelchair. The MIT damped joystick is an example of a four-degree-of-freedom device designed to aid in the control of a wheelchair by people suffering from tremor [11]. CEDO (Controlled Energy Dissipation Orthosis) developed by Rosen and colleagues is a three-degree-of-freedom grounded device that can be attached to a wheelchair or table permitting assistance for activities on a table. The device applies a velocity-proportional resistance to the forearm driven by particle brakes controlled by a computer. Experimental results with the device have reported a considerable tremor reduction with tracking tasks [12]. The only commercial available grounded device to assist in eating activities is the “Neater Eater” manufactured by Michaelis Engineering. The device is a two-degree-of-freedom, counter-balanced spring-based linkage arm that lifts and brings a spoon to an adjustable position near the mouth, eliminating uncontrolled movements [13].

The most far-reaching study on wearable orthosis has been introduced by Kotovsky and Rosen [5] with a viscous damping orthosis mechanism (Viscous Beam). Their mechanism works by applying a viscous resistance to motion at wrist level. This single-degree-of-freedom device reduces flexion/extension tremor amplitude by means of a constrained-layer-damping system able to damp rotary deflections of the wrist. A bending transmission converts flexion/extension of the wrist to linear displacement within the damper. Initial experimentation with the Viscous Beam showed that although the compactness of the device allowed for damping of tremor with some degree of amplitude, the device added elastic stiffness to normal movements and concluded that the device needed to be customized to each individual.

Conducting Polymer Actuators

Conducting polymers, such as polyacetylene (PA), polyaniline (PANI), and polypyrrole (PPy), first attracted attention because of their high electronic conductivities (approaching metallic conduction), and because their mechanical, optical, and chemical properties turned out to be controllable for certain systems by varying the redox state [14]. The process is described as the reversible doping and undoping of the polymer, since it involves the motion of cations and/or anions into sites in close association with the backbone of the polymer.

The possibility of using the change in mechanical properties (primarily volume and length changes) was recognized as making possible *electro-chemo-mechanical* actuators, or “artificial muscles [15]. One advantage of using conducting polymers is that the actuation process is identical to charging and discharging of a battery; therefore, the voltages involved per single cell are small (in the range of 1-5 V). A second point relevant to the suppression of tremor in humans is the relative softness of these actuators, which may make them especially suitable for use in conjunction with human limbs.

Significant research has targeted maximum volume expansion–especially in the form of a large linear extension [16]. For a free-standing PPy

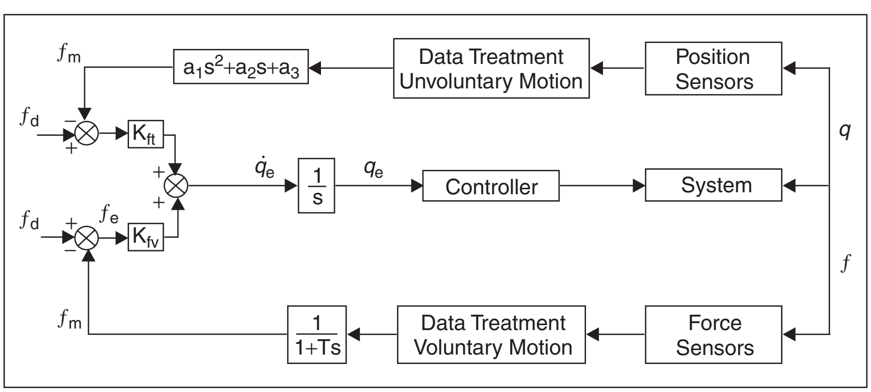

Fig. 10. The control architecture.

film, a maximum strain of 12% at a load of 0.5 MPa by combining a choice of materials with optimized conditions of synthesis, and by forming the polymer actuator on a compliant, micro-structured gold electrode. However, the large extension is only possible at slow contraction times. The strain decreases to a few percent at contraction times of ca. 0.1 s, which is slower than required for tremor suppression. If the limiting factor for the speed is the diffusion of ions from the electrolyte into the polymer, the polymer may have to consist of very thin layers or of fibers that may be difficult to manufacture or to handle. The limits to the speed of the actuation have been explored up to 30 Hz, using the bending beam technique, but the calculated volume change diminished by a factor of about 10 [17].

Our results in the present project indicate that it may be possible to reach higher frequencies, while retaining significant forces, by disregarding the goal of large linear extensions and instead use the difference in strength and stiffness between the oxidized and reduced states [18]-[21]. The Young's modulus of PPy can vary from 1.82 GPa in the freshly polymerized, dry state, to 0.54 (oxidized) and 0.18 (reduced) [19]. The stiffness is probably strongly dependent on the content of water, since water molecules enter the film along with cations during reduction. It has turned out that the time constant for this change is considerably smaller than that for the length change; probably because the large extensions are mainly caused by allowing time for the maximum number of water molecules to enter the actuator. This is a slow process. However, this state of the film is also associated with rather low strength; therefore, the loss of actuation by ignoring it is not so large.

Figure 11 shows the load difference measured for a 10-µm PPy(DBS) film, 3 mm wide [20]. Surprisingly, the load difference at first increases, and it only starts to decrease after scan rates larger than 1 V/s, corresponding to ~0.5 Hz. This encouraging result may stem from the more rapid sweep rates preventing the polymer to equilibrate into longer and softer conformations, as well as avoiding the large influx of water molecules. Our best results indicate that a force difference of 1 kg would require an actuator film 30-mm wide and 0.14-mm thick.

If significantly higher sweep rates are to be obtained with significant forces, it will be necessary to overcome the limitation caused by the ionic diffusion inside the bulk polymer. In order to develop PPy-based polymers with these favorable characteristics, a synthetic program to generate a wide range of pyrrolic-monomers is underway in conjunction with subsequent electropolymerization and materials characterization. A number of three-substituted pyrroles featuring a variety of functional groups (ketone, alkyl, carboxylic acid) have been synthesized (several pyrrole monomers from this study are shown in Figure 12) and electropolymerized.

Following electropolymerization, PPy-derivative films were produced with thicknesses in between 11 µm for poly(3-α-ethyl acetic acid pyrrole) and 60 µm for poly(3-α-decyl acetic acid pyrrole (monomer 4). The Young's modulus of the polymeric films was measured both in the dry state and when submerged in electrolyte solution (NaCl/H_2O) and in the case of poly(3-α-decyl acetic acid pyrrole) 4 (thickness ≈ 60 µm) was found to be 28 MPa and 10.5 Mpa, respectively. This drop in Young's modulus can be assigned to a softening of the polymer due to partial swelling in water [21]. At constant potentials, the Young's modulus of poly(3-α-decyl acetic acid pyrrole) was found to be 15.5 MPa in the oxidized form (0.5 V) and 15 MPa in the reduced form

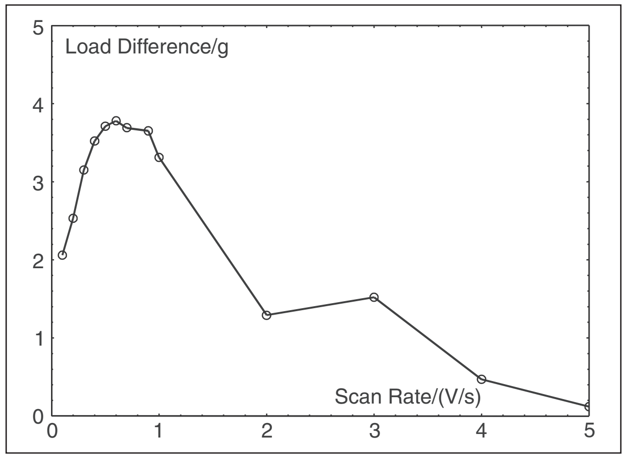

Fig. 11. Maximum difference in measured load between oxidized and reduced states for 10 µm PPy (DBS) actuators as a function of scan rate. Maximum load corresponds to 1.1 MPa.

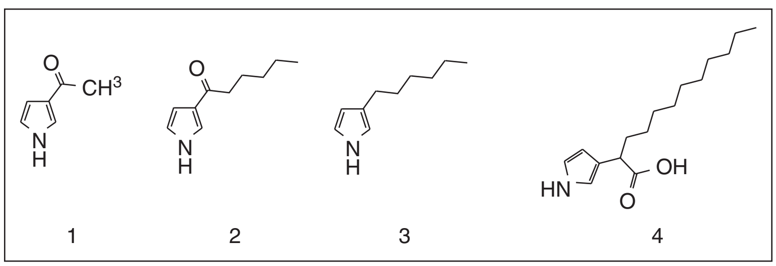

Fig. 12. A representative sample of the range of pyrrole monomers synthesized in the optimization of the PPy films.

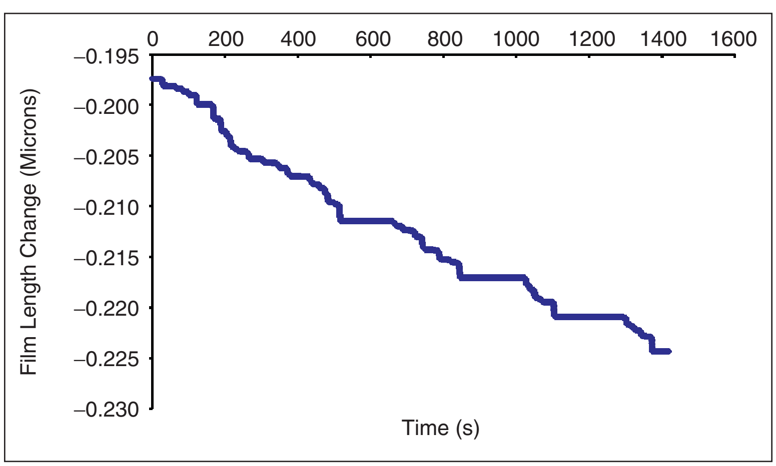

Fig. 13. Length change of a film of poly(3-α-decyl acetic acid pyrrole) when redox cycled in 0.1M NaCl solution loaded with a constant force (0.5M).

(-0.9 V). A constant force of 0.5 MPa was applied to the polymer film upon redox cycling and length changes were recorded over the duration of the cycling. The length changes observed for poly(3-α-decyl acetic acid pyrrole) 4 under these conditions are shown in Figure 13.

It is appreciable from Figure 13 that the strain on the film is mainly an expansion (creep) of the film upon cycling. This creep phenomenon is seen regularly at slow cycling rates, but it is usually supplemented by contraction. No net contraction is recorded for this sample, although the regular change in slope shows that an insertion/expulsion process does take place. It is not, however, strong enough to overcome the slow creep. This indicates that ion mobility within the polymer film must be limited. The low ion mobility may be a result of the thickness of the polymer film that corresponds to six times the thickness of a normal poly(pyrrole) film tested in similar conditions.

In conclusion, the preliminary studies upon PPy films and derivative polymers have revealed interesting frequency response behavior of the films in addition to unique strength characteristics. Future developments will concentrate upon the development of new Ppy systems either incorporating new pyrrole monomers or copolymer architectures.

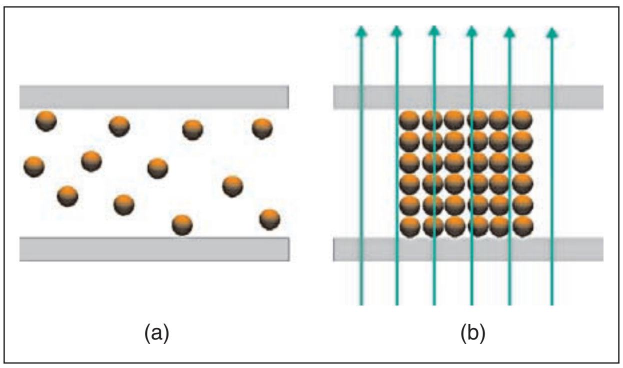

Fig. 14. Magneto rheological fluid behavior. Small iron particles are suspended on oil-based solution. (a) No magnetic field applied; (b) particles align forming bridges on the direction of magnetic field lines.

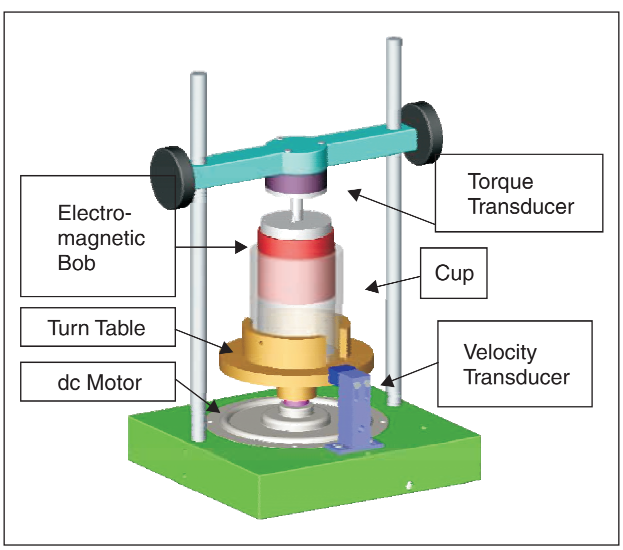

Fig. 15. MRF viscometer showing different components.

Properties of Magneto Rheological Fluids (MRFs)

MRFs: What They Are and How They Work

MRFs were developed in 1948 by Jacob Rabinow at the U.S. National Bureau of Standards [22]. MRFs are materials that respond to an applied magnetic field with a change in rheological behavior; i.e., fluids will change from liquid to almost a solid. MRFs in the simple form consist of small iron particles suspended on an oil-based solution (Figure 14). When at initial state (no magnetic field), particles are dispersed and the MRF behaves like a normal fluid. When a magnetic field is applied, the particles start moving from a dispersed state to form bridges in the directions of the magnetic flux lines. Depending on the concentration of iron particles suspended on the oil solution and on the strength of the magnetic field, it is possible to change the behavior of the fluid from a pure Newtonian liquid to almost a Bingham plastic.

These fluids are attractive as interfaces between mechanical and electronic control systems because of their ability to provide simple, quiet and rapid response to those signals. MRFs have been successfully used in a variety of applications ranging from automotive parts (engine mounts, shock absorbers, and seat dampers), vibration control and damping (earthquake resistant structures are built that utilize these fluids using semi-active control), and recently in medical applications such as prosthetics (above-the-knee prosthesis), exercise equipment for rehabilitation of limb muscles in physical therapy [23], [24] to most notably in cancer therapy (MRF injected into blood vessels and magnetic field applied externally in order to block blood flow to the tumor, creating its death) [24].

Design Considerations for MR Fluid Characterization

MRFs have been used in different applications, but still there are some fundamental issues to be solved, such as hard settling of the iron particles when fluid is left unused for some time and in-use-thickening. When fluid is subject to high stress and high shear rates over a long period of time, the fluid will thicken. Lord Corporation claims to have solved the problem, but the solution has not been published [25].

The need to develop a suitable fluid to be used in a controllable passive actuator-based orthosis has led to the development and characterization of several fluid recipes. The literature shows poor data on MR fluid characterization, and probably the most acceptable study carried out has been done by Dan et al. [26] for measurements of yield stress using tubes. This technique, however, does not allow for control of the magnetic field direction, which is an important aspect of MRF characteristics. Due to the lack of research (or commercial available product) that addresses the above issue, a dual-type axial symmetrical viscometer testbed has been designed that allows for both cylinder and parallel plate rotational viscometry. The current design (Figure 15) allows for measurements of shear stress, shear rate, yield stress, and fluid life cycle. In addition, the device also allows for measurements of fluid viscosity change as a function of an applied magnetic field and results can be taken with the generation of magnetic fields parallel or perpendicular to the direction of fluid flow.

Current and Future Work

Ongoing work concentrates on characterizing several MR fluid recipes using the framework described in the previous sections of this article. Experimentation with several fluid combinations and additives strives to find the best possible fluid properties to be used as an actuator/sensor using the inherent properties of MRFs in direct shear mode. A second stage is on the design of low-profile, controllable passive actuators that will work on the principle of viscous loading applied directly onto the surface of the skin and transmit forces to the bones.

Ergonomics

Primary Considerations

A priority consideration in this project is incorporation of the principles of "Design-for-All," thus allowing the widest possible user ability coverage. Consequently, the research study includes data collection for anthropometrics (Figure 16) and biomechanics measurements, to take into account consideration for the variances in expected data. This includes human variance across all sense modalities, disabilities, and cognitive abilities, as well as physical attributes, including age, gender, visual impairment, auditory impairment, ethnicity, and geographical location.

Control and Power Supply Unit Enclosures and Accessories

This project calls for an ergonomic designed enclosure for the control and power supply unit that will withstand normal everyday use and will comply to safety standards as laid out by the medical directives. A twin-case system, conforming to the body's natural contours and comfortable to the user, will be designed to accommodate the electronics and power supply. The enclosure would ideally adhere to the international standards for protection classification using the standard IP 2 digit recognition. The enclosure will require a belt or strap to attach the unit to the user by hip or waist belt. The suggested prototype enclosure is shown in Figure 17.

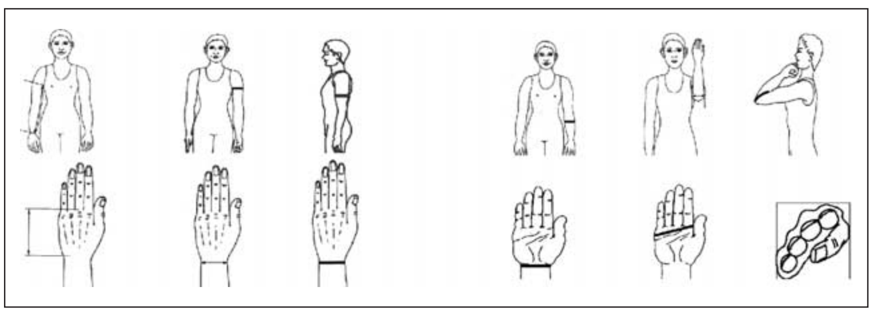

Fig. 16. Anthropometric data collected for the adult, older adult, and younger generations, including geographical location, percentile, and definitions.

Textiles for Wearable Orthoses

Objectives

The objectives are the following:

- identification of support structures that conform to the body shape at an acceptable pressure to allow contact of sensors to the body and to be thin enough to be worn under ordinary clothing
- identification of fabric types that do not cause excessive perspiration build-up both for comfort and degradation to the sensors and actuators.
- implementation of a design that will allow sensors to be easily attached and can be readily changed for integrated development.
- determination of the launderability of the design with regard to reuse, durability, and wear comfort.

So far, our work has focused on the following aspects:

- review of textile materials worn next to the skin.
- spacer fabrics produced into supports and tested on volunteers.
- testing thermal insulation, wicking, water vapor permeability, fabric shear
- pressure applied using the Hatra and Salzmann pressure tester leg.

Textiles Worn Next to the Skin

Fabric construction is important for fabrics worn next to the skin. The construction is said to influence the "feel" or soft-

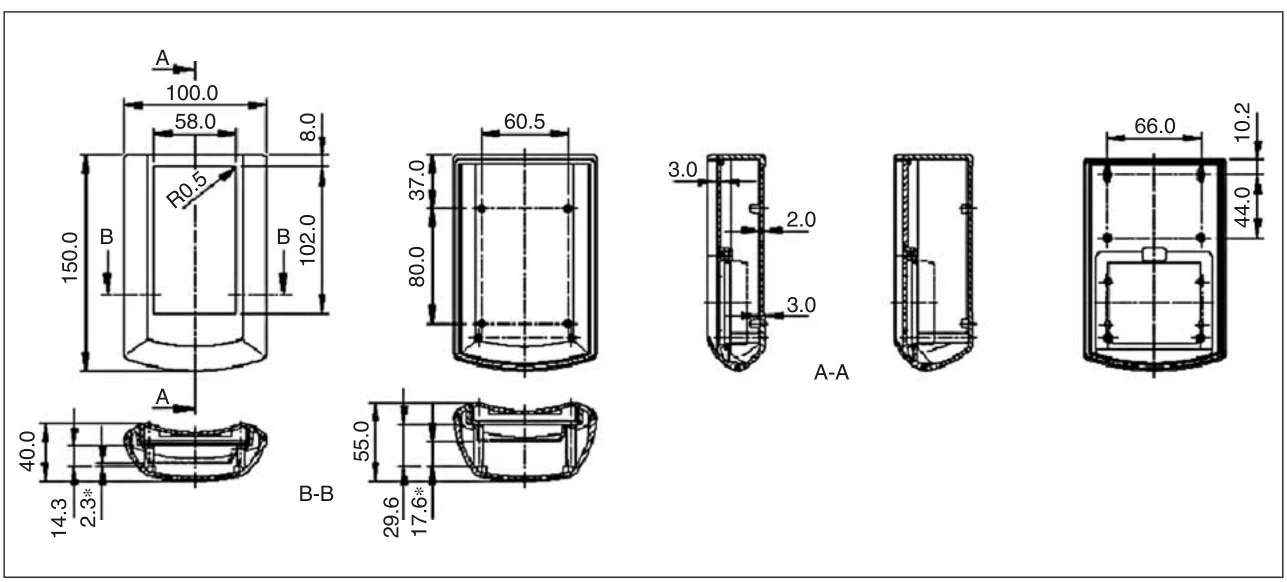

Fig. 17. Suggested control and power supply prototype enclosure.

ness of the fabric against the skin and the fabric's ability to wick moisture away from the skin. Skin sensitivity is an important consideration in terms of comfort. Different finishing and dyeing chemicals as well as detergents and conditioners used for the finishing and maintenance of textiles and clothing may cause allergies in sensitive persons. The composition and feel of a fabric itself can cause aggravation and a reaction to supersensitive skin. Mechanical abrasion such as a zip, Velcro, or a seam rubbing against the skin can cause skin irritation to occur; therefore, it is important to consider how the arm support is attached.

Fabrics that are suitable for wearing next to the skin must be comfortable and dry. Cotton is comfortable; however, when it is worn for long periods of time next to the skin, perspiration is absorbed by the fabric and the fabrics may feel moist and uncomfortable next to the skin. It is common to feel a chill after exercise if a cotton garment was worn, known as postexercise chill. Cotton is one of the preferred fabrics worn next to the skin, but when tight fitting it gives problems due to its high moisture retention, which can lead to a wet sensation. If sweat is trapped against the skin, irritation and skin swelling and softening can occur along with malodor. Some of the newer fabrics that afford good moisture management include Coolmax, Aquaduct, X-Static, etc. Some of these can also contain antibacterial materials to help prevent odor.

Woven structures can be produced in a wide variety of weights and weaves to create a rigid effect; however, with the insertion of elastane yarns, they can be given a degree of stretch and recovery for form-fitting garments. Warp-knitted structures are the predominant leader in the pressure garment market, with Powernet and Sleeknit constructions of polyester or polyamide and elastane being favored.

Among the many fabrics considered, the use of silver fibers is being studied further such as X-Static silver fibers. Silver is widely recognized as a safe and effective broad spectrum antimicrobial agent for infection control. The high electrical conductivity rate of this fiber suggests it would be beneficial to be used to seal the actuator and beam elements of the tremor support away from external influences such as mobile phones and hearing aids, which may cause interference.

Three-dimensional warp knit spacer fabrics have been considered by De Montfort University (DMU) as a possibility and have been investigated further. These fabrics consist of two surface fabrics that are connected by pile yarns used as spacers. This design creates a ventilated layer of air, allowing heat and moisture to escape.

Spacer Fabrics Produced into Supports and Tested on Volunteers

DMU has contemplated the use of spacer fabrics as the way forward. Fourteen spacer fabrics have been selected from a range of suppliers for investigation. The fabric compositions vary from 100% polyester, 93% nylon/ 7% Lycra, and varying percentages of polyester/cotton. The fabrics were produced into simple support bandages in order to assess each fabrics level of comfort against the skin. The bandages were each worn by two of the seven willing volunteers underneath ordinary clothing for a day. The volunteers were given a simple questionnaire asking what they thought of the material in terms of warmth and skin irritation. The idea of this experiment was to gain an initial feel as to whether spacer fabrics were welcomed and initial thoughts on fabric thickness, stiffness, and composition preference. The design aspect of the support was also questioned with volunteers highlighting potential problem areas that might cause irritation, restriction of movement, excessive warmth, and perspiration.

The design of the tremor support has been modified during these experiments, taking into account the comments of the volunteers. Combining a spacer fabric with a highly extendable material has been considered, which offers a better fitting support with more freedom of movement. It was noted that a great difference was found by the volunteers when a stretch panel was placed over the circumference of the elbow allowing the elbow to bend easier. Ways of fastening the support have been studied; however, further work needs to be carried out when more information has been given regarding the actuator and sensors.

Testing the Orthosis Support Structure

Many tests are recommended to be carried out on selected fabrics that may be suitable for the DRIFTS project. Initial tests required at this stage of the project include thermal insulation, wicking, water vapor permeability, and fabric shear. The 14 spacer fabrics have been subjected to testing to assess their suitability as a fabric used against the skin underneath clothing, supporting actuators and sensors. Initial results suggest that the spacer fabrics have similar properties and follow the same trends. Water vapor permeability decreases with fabrics thickness, and tog rating increases with fabric thickness. The fabrics, however, do not show any distinct trend when comparing the fabric thickness with thermal conductivity, fabric thickness and wicking, or fabric shear and thickness. Stiffer fabrics without elastane reduce shear while maintaining breathability. Further testing of fabrics need to be carried out to determine suitable fabrics for the support taking into consideration further developments in the actuators and sensors.

Conclusions

We have presented here an integrative multidisciplinary approach aiming to create proof-of-concept prototypes of wearable active orthoses for the suppression of upper-limb tremor while preserving natural movement. This is a formidable challenge. In 18 months of activity, the DRIFTS consortium has succeeded in establishing the parameters and constraints for constructing workable and usable active orthoses. The DRIFTS project takes into account knowledge from neurological sciences and neural control of movement, research in biomechanics, signal processing and control technologies, sensors and actuators, ergonomics, and state-of-the-art in modern textiles.

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