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A wearable tremor-suppression orthosis

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Abstract--The Viscous Beam is a wearable tremor-suppression orthosis that applies viscous resistance to motion of the wrist in flexion and extension. The orthosis reduces tremor amplitude and is small enough to be worn under the sleeve of a shirt. Hand and forearm cuffs couple the damper to the user. The cuffs permit full thumb and finger motion, wrist flexion and extension, and forearm pronation and supination.

Damping is provided by a constrained-layer-damping (CLD) system, distinct in that it can damp large rotary deflections through a small bending radius. A bending-plate transmission linearly converts wrist extension/flexion to rectilinear translation within the damper. Bending deformation of two plates held a fixed distance apart within the transmission results in relative displacement along the lengths of the plates. A viscous fluid incorporated between the plates provides shear damping. Silicone fluids with viscosities as high as 10 million centistokes (cS) and shear layers as thin as 0.76 mm have been tested. With these parameter values, damping constants as high as 2.0×10^{-3} N-m/(°/s) have been measured. This testing was conducted with strain rates as high as 4,580°/s. The elastic stiffness of this beam was measured to be 4.1×10^{-2} N-m/°.

Key words: constrained layer damping, orthosis, rotary damper, tremor suppression/reduction/attenuation.

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INTRODUCTION

This article presents the design, prototype fabrication, and evaluation of a tremor-suppression orthosis, the Viscous Beam. In keeping with a need defined in the literature of disabling tremor (1), the primary goal of the project was to design a compact, wearable damper that improves independence in manual function by decreasing the wrist tremor amplitude of persons with tremor. An integrated damper and transmission system that can be worn under the sleeve of a shirt and that demonstrably reduces tremor has been developed. As a commercial product, the Viscous Beam could be manufactured in a small number of sizes and viscosities and fitted clinically to the limbs of users via custom-formable cuffs.

The most disabling form of tremor is the "intention tremor," exhibited during voluntary muscle contraction in many individuals with multiple sclerosis and head injury. Its amplitude may be sufficient to prevent a person from accomplishing tasks with acceptable accuracy. Intention tremor of wrist extension and flexion is characterized by a 3-4 Hz frequency and an amplitude as high as 30° (2). Among other effects, severe tremor prevents unassisted eating, drinking, writing, and personal care.

Less commonly disabling, but more likely to occur without other neurological symptoms that would make accurate hand control functionally irrelevant, is "essential tremor" (3). This diagnosis describes a primarily distal tremor that tends to be inherited (idiopathic familial essential tremor) and to worsen with age. Many people with essential tremor may be limited by it only in specific activities requiring particular dexterity. For a relatively small percentage of this population, in particular older people, it can cause major activity limitations.

It has been demonstrated that viscous damping can dramatically reduce intention tremor amplitude and help to restore functional limb control (1,4-19). The Viscous Beam provides viscous damping of the flexion/extension motion of the wrist and requires no external reaction forces (i.e., it is wearable). For a person with tremor actively generated in multiple degrees of freedom (DoF) of the upper limb, a more general tremor suppression orthosis would be needed to restore whole-arm functionality. It should also be noted that numerous issues remain to be investigated experimentally regarding the effects of sustained application of viscous resistance. Arnold et al. (7) notes that muscle fatigue, carryover of attenuation effects after damping is removed, and long-term strengthening of muscles due to orthosis-imposed exercise all require study.

By extrapolating from sparse published data on tremors and tremorogenic conditions, the authors estimate that a wearable orthosis for damping wrist tremors would have potential utility for between 160,000 and 1 million people in the United States (2,3,20-22). These numbers were derived by applying percentages related to severity distribution and to the presence of other disabling symptoms to overall population statistics for essential tremor and multiple sclerosis.

Essential tremor would account for two-thirds to three-quarters of the total estimated market. A survey of neurologists specializing in movement disorders conducted by Chen as part of this and related studies also contributes to this estimate. It showed that approximately 160,000 Americans have intention tremor in a distal, upper limb (22) of sufficient severity to warrant use of a tremor-suppression orthosis.

Review of Alternate Designs

The standard and most effective current treatment for tremor is the use of medication. Because the clinical phenomenological tremor classifications are not perfectly predictive of their success, drugs are typically prescribed on a trial-and-error basis in order of decreasing expected effectiveness. If success in reducing tremor is found, it must be weighed against side effects and the potential for addiction (3,23).

A hypothetically effective alternative approach to restoring upper limb function to a person disabled by tremor is to assist the limb with compensatory technology. This concept can be implemented in two ways. For the limb to produce usefully accurate motion, either the tremor must be decreased, or the task must be isolated from movements of the tremorous limb in a frequency-selective manner.

To isolate the task mechanically (i.e., without introducing a "fly-by-wire" robotic manipulator), the person must operate through a series linkage conceptually similar to suspensions used in the film industry to isolate cameras from the vibrations of their carriers. This concept, used in the context of tremor (24), can improve the accuracy of control of an end effector or tool (e.g., a spoon or pencil) in the presence of the user's movement disorder. Considering that the end effector is manipulated through a tuned, low-stiffness spring, tremor isolators are inherently limited. Tactile sensation is virtually eliminated; control of tool dynamics is rendered more difficult; tool force is limited by system compliance; and the linkage system is potentially intrusive. For these reasons, attenuating tremor motion at the limb is more attractive than isolating it.

Four designs have been published for tremor-reduction devices that act mechanically in parallel with the user: they are energy dissipaters that apply a shunt load to the limb from a base grounded on a frame of reference external to the user, such as a table top or wheelchair frame. These are fixed-base restraints. The first is a table-mounted device called the Neater Eater made by Michaelis Engineering (25). This device is a 2-DoF damped linkage that supports a utensil to assist eating. The remaining devices were developed by our research group at MIT to the level of alpha prototypes.

One device, the Controlled Energy-Dissipation Orthosis (CEDO), is wheelchair-mounted and provides velocity-dependent loading of the limb (7,8,13,19). It couples to the forearm through a splint and permits sufficient range of motion in 3 DoF to facilitate eating and other table-top activities. Each DoF is damped, with the damping computer-controlled in real time via magnetic particle brakes.

The MIT tremor group also developed to a working laboratory prototype a 6-DoF computer-controlled, energy-dissipating manipulandum called the MED (Modulated Energy Dissipation) Arm, to control arm motion. A version of this device is being developed for commercial availability (Boston Biomotion, Boston, MA). Its operation is similar to the CEDO; particle brakes damp each DoF under instantaneous digital control. One critical difference is that, unlike the CEDO, the kinematics of the MED Arm are such that the damping load can always be directed precisely opposite in direction to end point movement. Another is that the user's unimpeded range of motion will accommodate a much more extensive set of functional tasks.

Another product of the same laboratory is the MIT Damped Joystick, designed to facilitate the control of power wheelchairs and other proportionally controlled technology by people with tremor (26,27). 3-DoF and 4-DoF versions of the design have been patented (28,29). Each damps all available DoFs using only a single sealed chamber of viscous fluid. It has been demonstrated that the 3-DoF joystick substantially improves performance in pursuit-tracking tasks by persons with tremor (26,27).

Finally, although not related to upper-limb tremor, a study by the same group evaluated the effects of viscous loading on spastic gait, showing that this gait can be modified, and local joint kinematics improved, with the use of a damped lower-limb orthosis (10,16).

Aside from the Viscous Beam, only one other design for a wearable tremor-suppression device is known. This device, disclosed by Hall, uses the gyroscopic effect of a single rotating mass to inhibit tremor motion (30). The use of a single gyroscope will torsionally load the hand about an axis orthogonal to the rotational axis of the tremor; it does not act to damp the motion. Various problems exist for this device's operation and implementation, and it is not commercially available.

Design Goals and their Implications

The objective of the orthosis described below is to attenuate tremor motion without unacceptable resistance to voluntary movements. As noted above, it has been established experimentally that velocity-dependent loading usually has this effect. Additionally, mechanical loading can readily be adapted to the needs of an individual; it is noninvasive and need not be expensive. For these reasons, the investigators decided early in the design process to base the wearable orthosis on the application of viscous damping.

The design goals for what became the Viscous Beam were established in the MIT tremor research group through consultation with persons with tremor, their families, and care givers (31). Expressed in engineering terms, they are summarized here.

1. *Selective tremor reduction:* the orthosis should minimize involuntary oscillatory movements by applying linear velocity-dependent resistance to wrist motion with minimal effect on voluntary movement.
2. *Compliance:* the elastic stiffness of the orthosis should be minimized to avoid requiring that the user maintain significant force levels to hold the orthosis at a non-neutral angle.
3. *Safety:* the device should not harm the user during use.
4. *Comfort:* the orthosis should be comfortable; impose only minimal loads due to weight,

mass, and moment of inertia; should not produce unreasonable pressures on the skin; should not be offensive to the senses and should be ventilated.

5. *Interaction with the Environment:* the orthosis should not impair voluntary interaction with objects or snag clothing, hair, and the like. Ideally, the damper will be compact so that it rests close to the arm and have proportions comparable to the aspect ratio of the limb itself.
6. *Range of Motion:* the device should not limit the amplitude of voluntary wrist motion.
7. *Ease of Use:* the device should be easy to don, adjust, use, and remove.
8. *Economy:* the purchase and maintenance costs of the device should be minimized and not exceed what the market would bear.

Initially, a direct-drive rotary damper mounted at the flexion/extension axis of the wrist was considered as a load source. This configuration would have permitted damping without a transmission, but it was deemed unacceptable due to the problems it would have caused either by interfering with thumb articulation or with objects in the environment, depending on whether the damper was mounted laterally or medially, respectively. The implication of this decision was that the design must incorporate a transmission in addition to a damper to transmit rotary motion at the wrist to rotation or displacement at the damper.

Several designs were considered for remotely mounted dampers. A rotary damper mounted at the forearm would require only a simple belt and pulley transmission. Rotary dampers were, however, deemed unsuitable for use due to their bulky form: they could neither conform to nor mimic the shape of the arm. This decision not to use a rotary damper implied the use of a rectilinear damper, adding rotary-to-linear conversion to the design requirements imposed on the transmission.

Piston-in-cylinder configurations, based on commercially available hydraulic actuators, were initially considered for providing rectilinear damping. They could be driven by a simple connecting rod from the back of the hand cuff or with a closed belt arrangement to provide a constant moment arm at the cost of greater size and complexity. Several approaches were considered to permit customization, adjustment, or adaptive response of the damping coefficients of the dampers. Designs typically incorporated flow-restriction orifices. In one, they were self-adjusting to increase damping in reaction to recent repeated cyclic loading of the device. In another, the orifice size varied with piston position, permitting nonlinear damping (if necessary to compensate for geometric nonlinearities in the transmission). Although they offered some advantages, piston-in-cylinder devices were ultimately dismissed for their shape and bulk, that is, for their failure to meet design goal 5.

Alternate damper designs included a pneumatic damper and a dynamic absorber ("tuned-mass damper"). The former had the advantage of light weight but failed to meet design goal 1 because of its velocity-squared damping and the elastic loading contributed by the compressibility of air. The dynamic absorber concept fails most notably with regard to design goal 5.

A decision was made early on that comfort and functional unobtrusiveness (goals 4 and 5) merit major design emphasis so that orthosis users would not find that discomfort and inconvenience were obligatory costs of obtaining the benefits of the device. To support decisions regarding placement of the damper/transmission system for reduced interference with function, ad hoc trials were conducted. One of the authors wore a mockup, similar in size, weight, and shape to a cylindrical damper, for 24 hrs each on the dorsal, ventral, radial, and ulnar aspects of the forearm, secured by an elastic bandage. It was provisionally concluded that the dorsum of the forearm is the most comfortable and functionally unobtrusive position for the device. This surface is least commonly used or contacted in functional interaction with oneself or the environment. The ventral and ulnar sides of the forearm proved to be the most uncomfortable surfaces; positioning the mechanism on the radial side of the arm hinders activity less than the ulnar or ventral sides, but interferes with full thumb motion.

To assure that the orthosis remains comfortable to wear while the damper dissipates tremor power, the heating of the damper has been estimated. We make two worst-case assumptions to establish an upper bound on power which must be dissipated. The first is that the tremor-generating muscle torque is not reduced with the addition of a tremor-suppression orthosis. The second is that all of the muscle's work in the presence of the orthosis must be dissipated by the orthosis: none is applied to the elastic and inertial load elements of the load. For a sinusoidal hand tremor motion of 3 Hz with a ±30° amplitude (severe tremor), the average power into the system can be found from:

$$P_{av} = \frac{\int_{0}^{cycletime} \mathrm{T}\omega\, dt}{cycletime} \quad (1)$$

where T is the muscle torque driving the wrist oscillation and ω is the sinusoidally varying angular velocity of the wrist found from time differentiation of the sinusoidal position expression. The torque can be found from:

$$\mathrm{T} = J\alpha \quad [2]$$

where J is the hand moment of inertia, determined to be 29 $kgcm^2$ from anthropometric measurements and α is the angular acceleration of the wrist found from time differentiation of the angular velocity expression. Under these assumptions, the average power that the damper will be required to dissipate is found to be 1.7 W. This value is low enough that it is clear that the temperature rise at the user's limb need not be uncomfortable.

In summary, for the wrist tremor-suppression orthosis, a small, rectilinear damping mechanism wearable on the dorsum of the forearm is desirable. The Viscous Beam design incorporates a very slender damper with a compact linear transmission, and can easily be worn on the dorsum of the forearm. Of the many designs considered, it was found to meet the goals of the project best.

The Viscous Beam Design

Both aspects of the Viscous Beam, the transmission and damper, were designed to allow the damper to be as slender (i.e., small in the dimensions normal to the long axis of the forearm) as possible. The development of the shearing plate concept, in preference to a more conventional drag element moving within a three-dimensional volume of viscous fluid, was driven primarily by this goal. For a linear, reciprocating motion, use of flat plates for damping, as opposed to any three-dimensional form, minimizes the thickness of the damper (normal to the limb) and the total mass of damping fluid required.

The flat plate damper is conceptually simple; two plates are arranged so the spacing between them is constant as they slide relative to each other. By placing a viscous fluid between the plates, a damping force is achieved as a consequence of motion. It is directly proportional to the area of the plates moving relative to each other and to the viscosity of the fluid. Since the shear stress on a fluid is given by

$$\tau = \mu \left(\frac{du}{dy} \right) \quad [3]$$

where *du* is the fluid-velocity differential parallel to the direction of fluid shear and *dy* is the fluid-height differential normal to the direction of shear, the shear rate of the fluid between the plates is

$$\frac{du}{dy} = \frac{\mathrm{v}}{\mathrm{H}} \quad [4]$$

where v and H are defined in **Figure 1.**

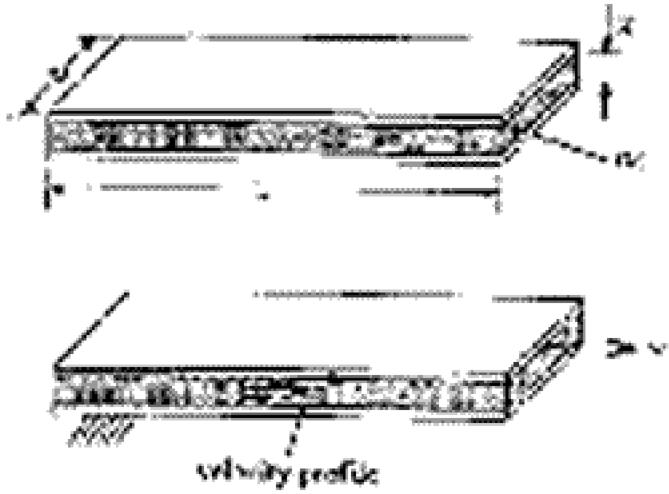


Figure 1. Single shear layer damper dimensions and velocity profile.

The damping force of the mechanism, F, is the product of the fluid shear stress and the plate areas:

$$F = \tau L W = \frac{\mu v L W}{H} \quad [5]$$

Thus, by minimizing the spacing between the plates and using a highly viscous fluid, a very compact flat damper may be created. While decreasing size pays off in terms of both unobtrusiveness and higher damping, a practical limit on decreasing the separation of the plates is set by the accuracy with which very small spacing between them can be maintained. This is determined by the shape and material characteristics of the plates. Another limit derives from the characteristics of the damping fluid.

Bending Plate Transmission

To meet our requirements, the bending plate transmission must map rotary motion of the wrist to rectilinear motion of the damper, according to a linear function. If the transmission does not provide a linear transformation, the damper would subject the wrist to position-dependent loads. While data from in-use experimental evaluation might establish that functional loss (or benefit) results from a nonlinear function, in the absence of that data, the design goals called for a linear function. The following section describes the principles upon which the bending plate transmission operates.

The transmission consists of two plates joined at one end by a spacer and constrained in such a way that they remain separated by a fixed distance along their lengths. When bent elastically, a slight motion between the plates results from their different bending radii. The related velocities are depicted in **Figure 2.**

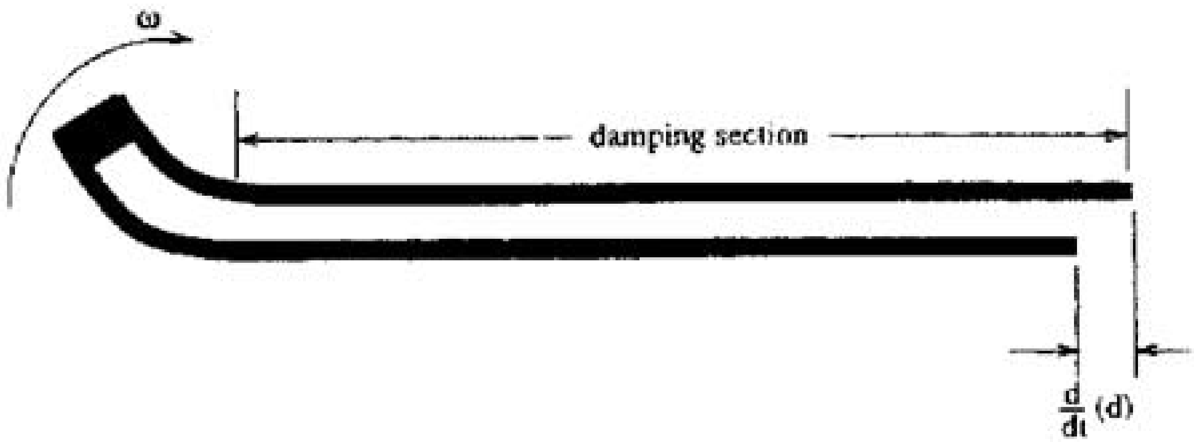


Figure 2. Demonstration of the offset resulting from bending plates at different radii. The offset, d, is directly proportional to the separation, *S*, of the plates.

The velocity of the relative plate motion is directly proportional to the angular velocity at which the joined ends of the plates are bent. The following calculations in **Figure 3** demonstrate this: S is defined as the (constant) distance between the neutral axes (mid-thickness lines) of the plates; and R and r are also measured to these axes so that $S=R-r$. Further, $L=R\theta$, the arcwise length of the outer plate, treated in this derivation as constant without loss of generality. Similarly, $l=r\times\theta$, the arcwise length of the curved portion of the inner plate which subtends the same angle as L.

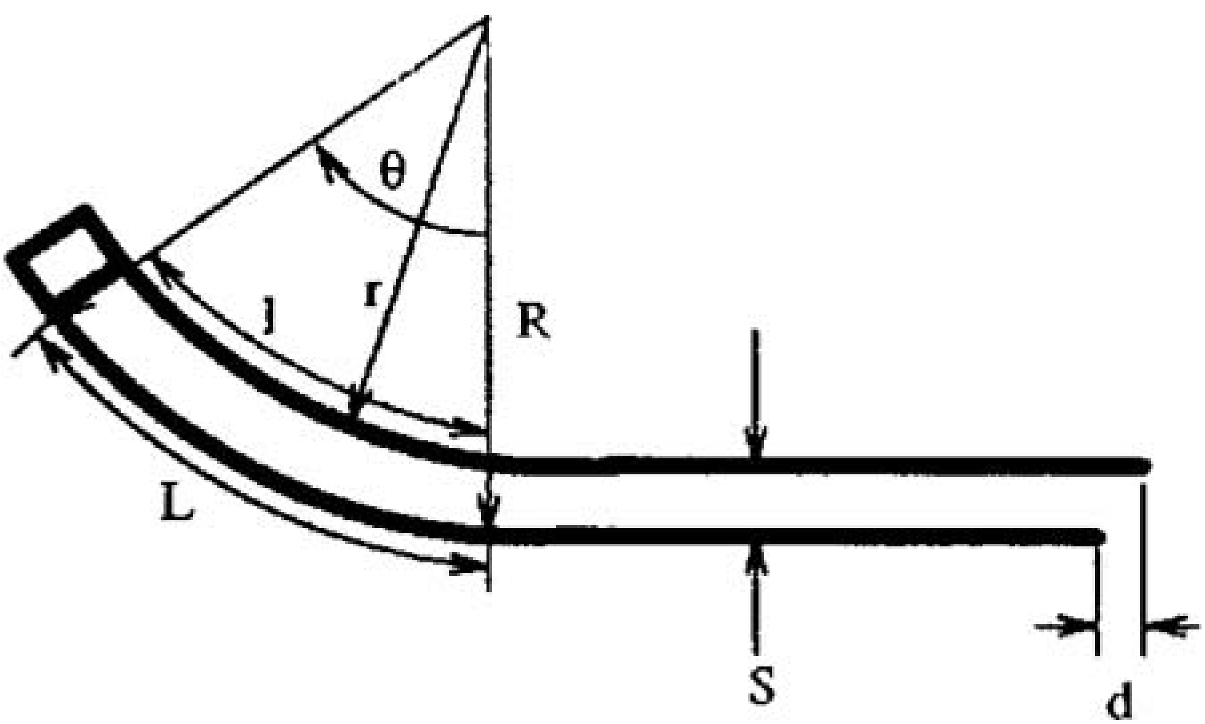


Figure 3. Dimensions of the transmission.

So $l = (R - S)\,\theta$

and $R = \dfrac{L}{\theta}$,

so that $l = L - (S\,\theta)$.

Differentiating gives
$$\frac{d}{dt}(l) = \frac{d}{dt}(L) - \left\{S\,\frac{d}{dt}(\theta)\right\} - \left\{\theta\,\frac{d}{dt}(S)\right\}. \quad [6]$$

But $\dfrac{d}{dt}(S) = \dfrac{d}{dt}(L) = 0$;

and $\dfrac{d}{dt}(l) = \dfrac{d}{dt}(d)$ since the inner plate extends past the outer by the same amount that l shortens relative to L.

Hence $\dfrac{d}{dt}(d) = -S\,\dfrac{d}{dt}(\theta) = -S\omega$

Thus, we see that the linear relative velocity of the plates is proportional to the angular velocity with which their joined ends are bent. The center-to-center distance between the plates is the constant of proportionality.

In the presence of viscous fluid between the plates, then, their relative motion (during bending) induces the velocity-dependent resistance:

$$F = \mu L W \frac{S}{H}\,\omega \quad [7]$$

By simply bending the plate/fluid sandwich, a resistive force proportional to the rate of angular deflection is realized. In other words, a transmission is provided between the rotational motion of the joined end of the plates and the rectilinear damper comprised of their undeformed lengths. The damping constant is determined by the surface area of the plates, the viscosity of the fluid, and the ratio of the center-to-center spacing to the fluid film thickness.

Construction of the Viscous Beam

Several working prototypes of the Viscous Beam have been constructed that span a range of damping constants. **Figure 4** shows a formal drawing of a representative version of the base plate of the design, and **Table 1** presents descriptive parameter values for that unit. The top plate, a simple piece of flat stock, is not shown in **Figure 4.** It connects to the base plate via four fasteners through the holes shown. The top plate tracks in the channels shown in the damping section of the base, leaving a 0.76 mm gap beneath, in which fluid is sheared. The overall lengths of the prototype beam designs are all in the range of 200 mm.

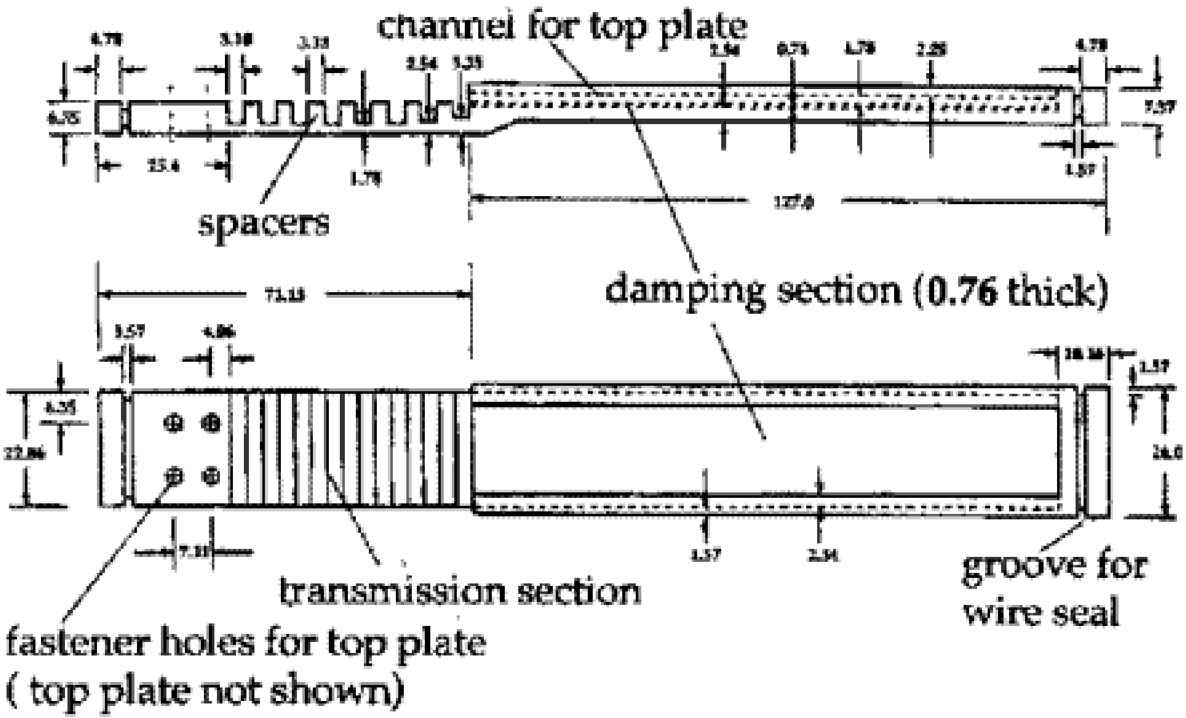


Figure 4. Drawings of the Viscous Beam; dimensions in mm, material: Teflon.

Table 1.
Prototype orthosis characteristics.

Parameter	Value
Weight with cuffs	2.6 N
Overall length with cuffs	25.4 cm
Thichest portion over forearm	2.0 cm
Length of forearm cuff	11.4 cm
Thickest portion over dorsum of hand	2.2 cm
Maximum deflaction	±90°
Maximum damping for this prototype	2×10^{-3} Nm/(deg/s)

The lateral grooves cut in the transmission section of the base plate leave standoffs for the top plate while decreasing the elastic stiffness of the beam. The grooves are wide enough to permit greater than ±90° of flexion/extension of the Beam, allowing a full range of wrist extension/flexion.

All of the prototypes were fabricated from teflon because of its ease of machining and its inherent visco-elastic properties. Its melting temperature is over 230 °C, so that burrs (as a result of melting during machining) are not a problem at normal machine feed rates. Since the concerns in the prototype phase are typically different from those that govern large-scale manufacture, other materials might be used in place of teflon if the Viscous Beam is manufactured in quantity. Regardless of material choices, however, dimensions must be scaled so that the product of the second moment of inertia and the modulus of elasticity of the plate is sufficiently high to resist buckling (dependent on the damping constant and maximum angular velocity during use).

Covering

For this design concept to be reduced to practice, fluid between the upper and lower plates must be prevented from leaking out. It is also important to keep the fluid free of debris and air to maintain consistent and predictable damping. For these reasons, an airtight wrapping must surround the fluid. The material chosen must be durable and easily cleaned.

Air in the damper is undesirable for two reasons. Air pockets between the plates of the damper displace the silicone fluid, decreasing the area of contact between the plates and the fluid, resulting in decreased damping. Additionally, air bubbles between the plates in the transmission are more elastic than the fluid, reducing the constraining forces on the plates and facilitating their buckling.

Within the transmission portion of the damper, it is critical to the geometry of the design that the plates remain a fixed distance from each other while bending. The standoffs machined into the transmission end of the base plate set the minimum spacing between the plates but do not prevent the plates from separating. The plates tend to separate as the transmission is flexed and the fluid volume sheared. The plate on the inside of the bend is in compression and will buckle if the force (proportional to the angular velocity of bending) is sufficiently high. The plates' area moment of inertia could be increased to prevent buckling, but the stiffness of the system would also increase, an undesirable effect for this application. If, in other applications, a beam stiffer in bending is acceptable or desirable, the thickness of the plates can be increased to provide added stiffness along with resistance to buckling. To minimize the elastic stiffness of the present system, two alternate methods are used to prevent plate buckling.

Fluid is included in the transmission (bending) section of the damper as well as in the rectilinear section to help to prevent plate buckling. For the top plate to buckle and separate from the spacers, fluid must fill in the original position of the plate or a void will be formed. The fluid's resistance to flow helps to prevent the separation.

The second and more effective means of preventing plate separation is to elastically restrain them. By covering the transmission section (bending section) of the damper with a stiff elastic membrane, the plates are much less likely to buckle. The elastic film contributes a clamping force orthogonal to the surfaces of the plates to prevent buckling. The film's contribution to the bending stiffness of the transmission is very small (relative to increasing the plates' bending moment of inertia to accomplish the same end). The covering should clamp the plates radially while remaining relatively slack longitudinally (i.e., function like an accordion bellows).

Several flexible, elastic membranes were evaluated to meet the specifications listed above. From the standpoint of convenience of fabrication, the assembled damper (including the damping fluid) could be coated by dipping into a fast-curing liquid-rubber bath. An ideal cured rubber would completely coat the damper with uniform thickness to insure no fluid or air leakage. It would also closely conform to the damper to provide an elastic restraint for the plates. Silicone rubbers Q7-2213, 3110 RTV, HS II RTV, and 236 (Dow Corning Corp., Midland MI) were tested exhaustively, but the fabrication problems encountered at the interface of the damping fluid and the rubber coating could not be overcome. Among other problems, the flow of the fluid during the rubber curing cycle permitted the fluid to mix and flow with the covering, disrupting the integrity of the seal.

Pre-formed surgical tubing was found to offer many advantages over dip-applied elastomers. This latex product is very strong, tear resistant, and inexpensive. It is neither brittle nor prone to fatigue. It can be pre-stretched around the plate assembly and used in multiple layers to resist plate-buckling. An undersized inner diameter (ID) was chosen to provide the pre-stretch. 1.25 cm ID surgical tubing with a wall thickness of 1.6 mm is used to cover the Viscous Beam design shown in **Figure 4.** The tubing ends are sealed using stainless steel wire ties in the grooves machined in the teflon for this purpose.

Fluid

The fluid used for the device is a dimethyl silicone available in viscosities ranging from 5 to 17 million centistokes (cS). Selecting from among available viscosities allows the damping constant to be customized to optimally affect an individual user's tremor without changing the design or dimensions of the Beam. The damping constant specified for the prototype was based on experience with the MIT Damped Joystick, since that device was proven to attenuate wrist extension/flexion (among other DoFs) tremor. The maximum damping of the Joystick was measured to be 4.7×10^{-3} Nm/(°/s). To achieve nominally the same damping, prototypes were constructed with 5 and 10 million cS silicone fluids (S-7200 Fluids: McGhan NuSil Corporation, Carpinteria, CA).

Characterization of the Device

Test Methodology

Three prototype Viscous Beams (1×, 2×, and 4×) were tested to characterize their properties and to verify analytical expectations. The 1× was designed to produce the same damping as the MIT Damped Joystick, the 2× and the 4× to produce twice and four times that (see **Table 2**). These prototypes are identical except for the fluid used. Their damping and stiffness characteristics were measured using a computer-controlled 1 DoF robot known as CSCAT (developed for use primarily as a limb-loading manipulandum for tremor research). It utilizes a direct drive brushless motor with torque and position feedback (9). CSCAT was used to cycle the prototypes through a range of positions and velocities and measure the resulting dynamic torque. A least-squares fit was used to find the values of damping and stiffness coefficients which provided the best match of the data to a model spring-damper system.

Table 2.
Linear fit estimates for subsystem and overall stiffness and damping based on test results and analytical expectations for the overall system.

Component	Total Stiffness (Nm/deg)	Total Damping [Nm/deg/sec)]	Analytically Expected Damping [Nm/deg/sec)]
Teflon Plates	5.6×10^{-3}	3.5×10^{-4}	--
Teflon Plates and 1 latex layer	1.1×10^{-2}	5.2×10^{-4}	--
Teflon Plates and 2 latex layers	1.3×10^{-2}	7.0×10^{-4}	--
1× Complete	2.3×10^{-2}	1.5×10^{-3}	4.2×10^{-3}
2× Complete	2.7×10^{-2}	1.8×10^{-3}	8.4×10^{-3}
4× Complete	4.1×10^{-2}	2.0×10^{-3}	1.7×10^{-2}

For the sake of modeling, the components of the Viscous Beam were assumed to act as elements in parallel with no interaction effects. The teflon plates were modeled as a linear elastic element. The teflon's inherent damping was ignored because this material property was expected to be negligibly small, relative to the damping fluid. The latex tubing was also modeled as a stiffness element. The silicone fluid was modeled as a linear damping element. The simplified lumped parameter model is thus a combined elastic element (the sum of the two elastic elements mentioned) in parallel with the fluid damping element. The CSCAT was driven by a P.I.D. controller that followed a pseudo-random position input comprised of the sum of a series of sinusoidally varying position inputs (32). This insured that the plate was tested in a well-sampled velocity-position phase plane. The testing velocity range included velocities of severe tremor. The position range tested was limited to ±35°.

Throughout the velocity-position phase plane, the test program acquired 1,200 data points per experimental configuration; these were fitted to the lumped parameter model. The combined force of the damping and elastic elements of the Beam can be expressed as

$$F_{total}(x,\dot{x}) = f_{stiffness}(x) + f_{damping}(\dot{x}). \quad [8]$$

An equation for the force response of the Viscous Beam was derived from a least squares fit with basis functions $X_{1_j}(x)$ and $X_{2_j}(\dot{x})$ and defined to represent the line segments whose dependent-value endpoints are given by the aj coefficient set

$$F_{total}(x,\dot{x}) = \sum_{j=1}^{M_1} a_j X_{1j}(x) + \sum_{j=M_1+1}^{M_1+M_2} a_j X_{2j}(\dot{x}). \quad [9]$$

This fit gives M_1-1 linear segments in the torque position plot and M_2-1 in the torque-velocity plot (32). The (M_1+M_2) coefficients aj were solved for by the least squares method that produced simultaneous estimates for the torque-position and torque-velocity relations.

Test Results

The overall stiffness and damping of the Beam are affected by the geometry and material properties of all its components. To establish how each contributed to the Beam characteristics, various experimental configurations of materials were tested. The least squares procedure was performed for each experimental configuration to determine each isolated component's contribution to stiffness and damping. **Table 2** summarizes the test results for the Viscous Beam structure, that is, the pair of plates alone (of dimensions shown in **Figure 4**), with one and two layers of latex tubing, and the complete Beam including the damping fluid. The second layer of surgical tubing was applied to the transmission section of the beam to provide added resistance to buckling, as discussed above. Based on the lumped parameter model described, **Table 2** also presents the analytically expected damping. The damping values were calculated using equation 7 with the manufacturer's specified viscosities used for the different dampers. **Table 3** presents the contributions of each component to the total stiffness and damping of the prototype.

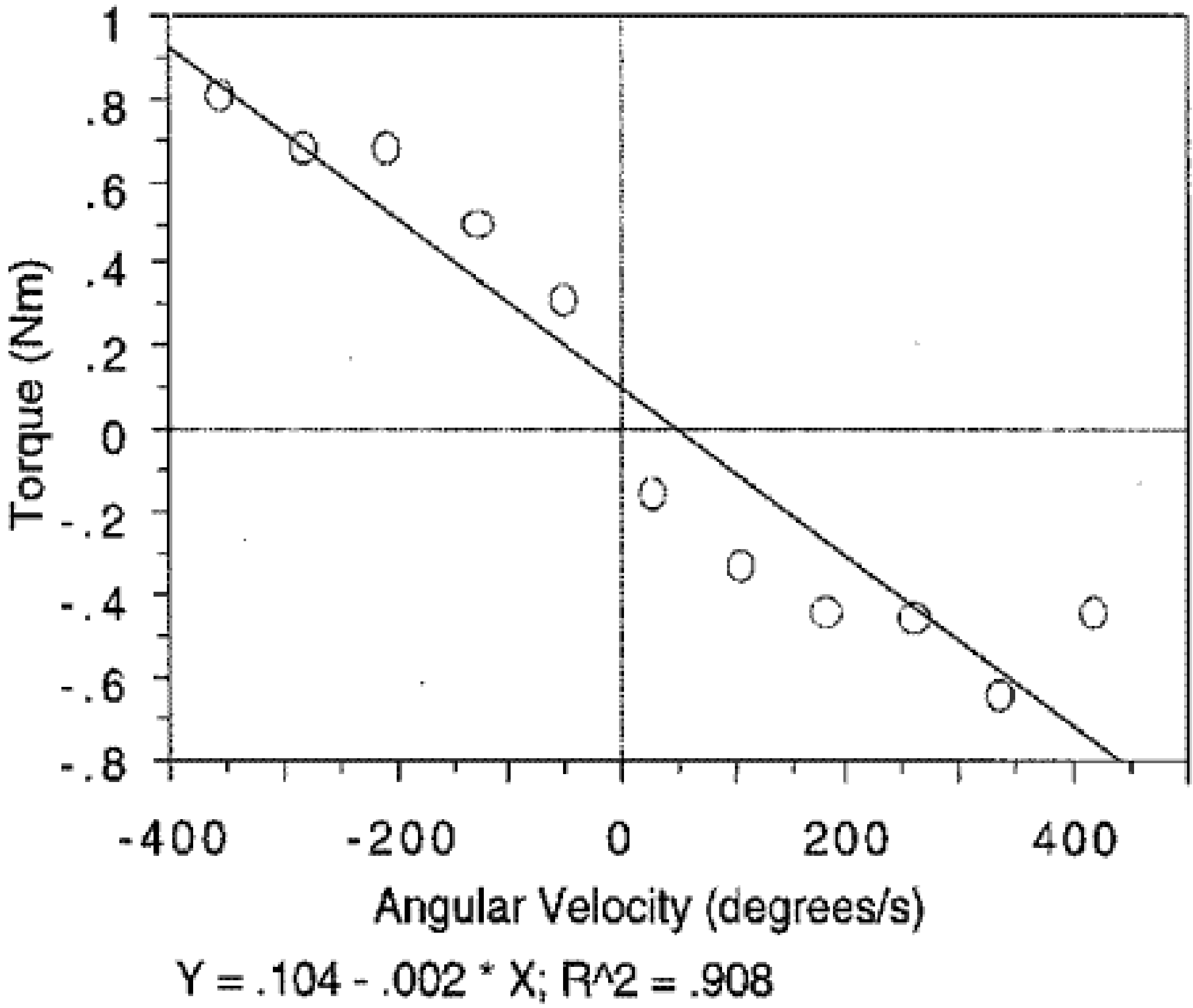
Table 3.

Component contributions to total measured stiffness and damping for the three prototype dampers (1×, 2×, and 4×).

	Percent of Total Stiffness			Percent of Total Damping		
Component	**1×**	**2×**	**4×**	**1×**	**2×**	**4×**
Teflon	24	20	14	22	19	18
Rubber	31	27	17	26	21	17
Fluid	45	53	69	52	60	65

Representative plots of the Beams' actual behaviors are given for the complete 4× damper in

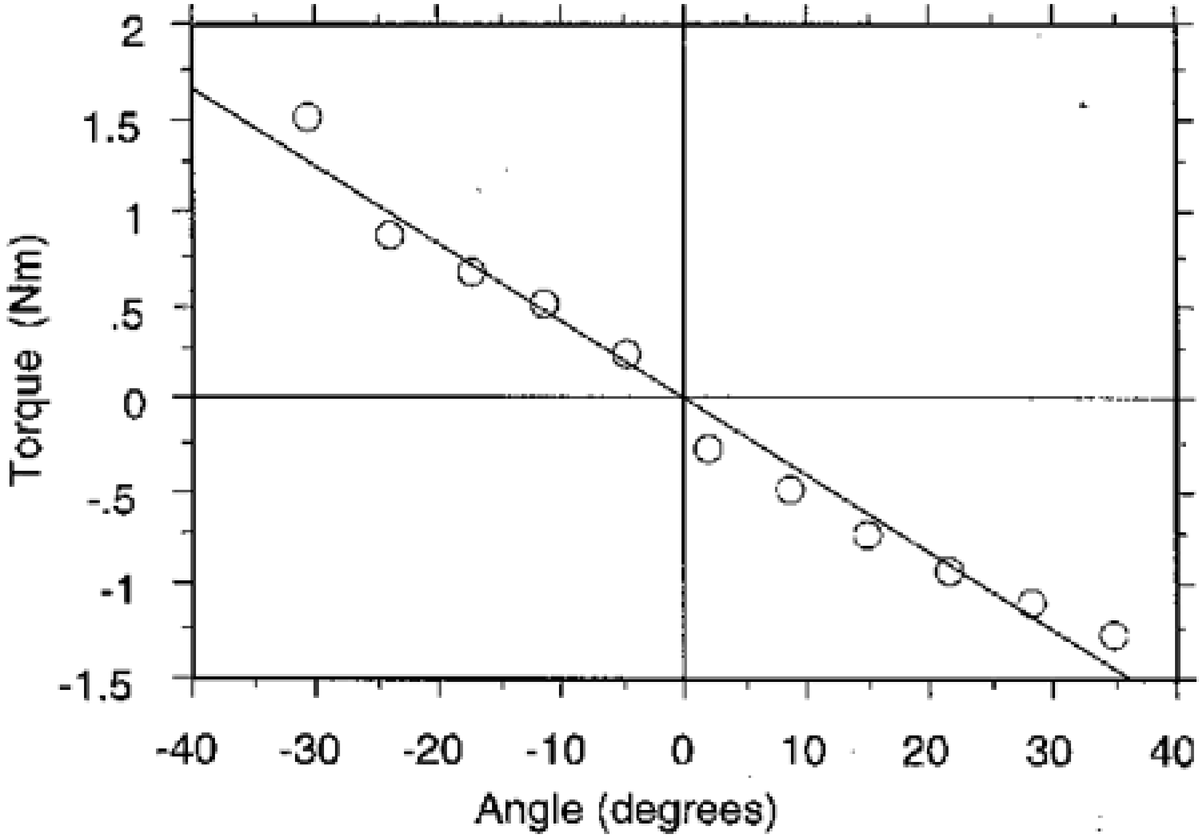
Figures 5 and **6,** which represent Beam resistive force as a function of angular deflection and angular velocity.



$$T = 0.104 - 0.002\omega$$

$$R^2 = 0.908, p < 0.0001$$

Figure 5. Damping characteristics of the 4× Viscous Beam.



$$T = 0.005 - 0.041\theta$$

$$R^2 = 0.977, p < 0.0001$$

Figure 6. Stiffness characteristics of the 4× Viscous Beam.

Interpretation of Results

As demonstrated by **Tables 1** and **2,** experimentation with the Beam did not produce analytically predicted results; the damping is three to eight times less than expected. Additionally, the nonfluid components of the device contribute significantly to the overall damping. Finally, the fluid contributes a large percentage of the total elastic stiffness.

The lower-than-expected damping values can be shown to be primarily a result of decrease in the viscosity of the fluid with its strain rate. For the fluids used in the devices, no documentation exists characterizing strain-rate-dependence. (Experimental characterization of the damping fluids was beyond the funded scope of this project.) Without this data, the accuracy of the theoretical models is inherently limited. It has been shown that the strain-rate-dependence is a result of decreased intermolecular friction due to ordering of molecules in the fluid with increased strain (33). While this characteristic is known to increase with molecular weight and fluid viscosity, testing by Dow Corning of dependence of viscosity on strain rate has been conducted only for silicones of lower viscosities (100,000 cS or less). The strain-rate-dependence of the 5 to 10 million cS fluids used in the Viscous Beam cannot be extracted from this information.

Summary description of the behavior of the prototype merited only a linear regression for the torque-velocity curve in **Figure 5.** Due to the strain-rate dependence of the fluid, a higher order polynomial would more accurately describe the torque-velocity relationship. A third-order polynomial fit (R^2=0.982), for example, shows a 51 percent increase in damping at small velocities. A fifth-order polynomial fit (R^2=0.984) shows a 101 percent increase in damping at small velocities. Although the velocity dependence of the fluid may not fully explain the Beam's deviation from expected behavior, these fits demonstrate that it contributes significantly.

In calculating the theoretical damping constants, the effects of the rubber and teflon were not included because they were expected to be small, relative to the total damping. From experimentation with the combinations of components, it is clear that there are interaction effects that contribute to the damping (and stiffness) of the Viscous Beam. An example of this is the latex rubber's contribution to damping; alone, the latex shows no apparent viscous behavior, but when stretched around the teflon plates (see **Tables 2** and **3**), it contributes a significant portion of the total damping.

Latex, when used as a covering around the teflon plates, contributed substantially to the bending stiffness. This was not intended and is not an inherent feature of the Viscous Beam design. This contribution could be reduced by modifying the fabrication of the damper so that the latex covering is not pre-stretched axially. For the units whose test results are reported here, the surgical tubing was cut 1.25 cm shorter than the Beam's length to prevent wrinkling (for aesthetics only) on the concave side during bending, and this pre-stretching resulted in increased beam stiffness, since the increment in tensile force on the convex side associated with an absolute increment of stretch depends on the fractional increase in length, relative to the unstretched length, imposed by that stretch. More pre-stretch indicates a smaller unstretched length and consequently a greater fractional stretch. If the contribution of latex stretch to bending stiffness needs to be further reduced, intentional pleating of the cover is possible, providing the necessary hoop tension without arcwise tension.

Testing also demonstrated the fluid has a strong elastic component that was not expected and not included in the lumped parameter model. (See the stiffness results in **Tables 2** and **3.**) An improved model of the fluid would include an elastic element in series with the damping element. Because the model does not include such a combination, forcing the data to fit this model may partially explain discrepancies between expected and obtained results.

Although the stiffness of the Viscous Beam is greater than initially anticipated, the stiffness loading is no greater than the viscous loading for tremor motions. For the tremor characteristics of 3 Hz and ±30° used in the heat dissipation calculations above, the peak viscous loading is the same as the peak load due to the elastic restoring force for the 4× damper. For smaller amplitudes of tremor at similar frequencies, the viscous loading exceeds the elastic loading.

The fluid viscosity's dependence on temperature may also contribute to the discrepancy between predicted and observed damping. With increased fluid temperatures, the viscosity of the fluid decreases logarithmically (34). For a 20° fluid-temperature increase from 20 °C, for example, the viscosity of the fluid used in the 4× damper decreases by a factor of 2. The temperature dependence of the viscosity must be compensated for on an individual basis, depending on the user's tremor characteristics (e.g., power to be dissipated) and expected use (e.g., in cold or warm environments).

The material and component properties described here do not permit the prototype to have a linear damping characteristic. However, despite the nonlinear behavior of the silicone fluid, it is the only appropriate ultrahigh viscosity damping fluid available. As noted above, until substantial evaluation data have been gathered with tremor-disabled users, it is not clear how the success of a tremor-suppression orthosis will be influenced by the observed variation in the damping constant.

Mounting Devices

In designing the tremor suppression orthosis, the interface of the damper with the user was carefully considered (refer to **Figure 7** throughout this discussion).

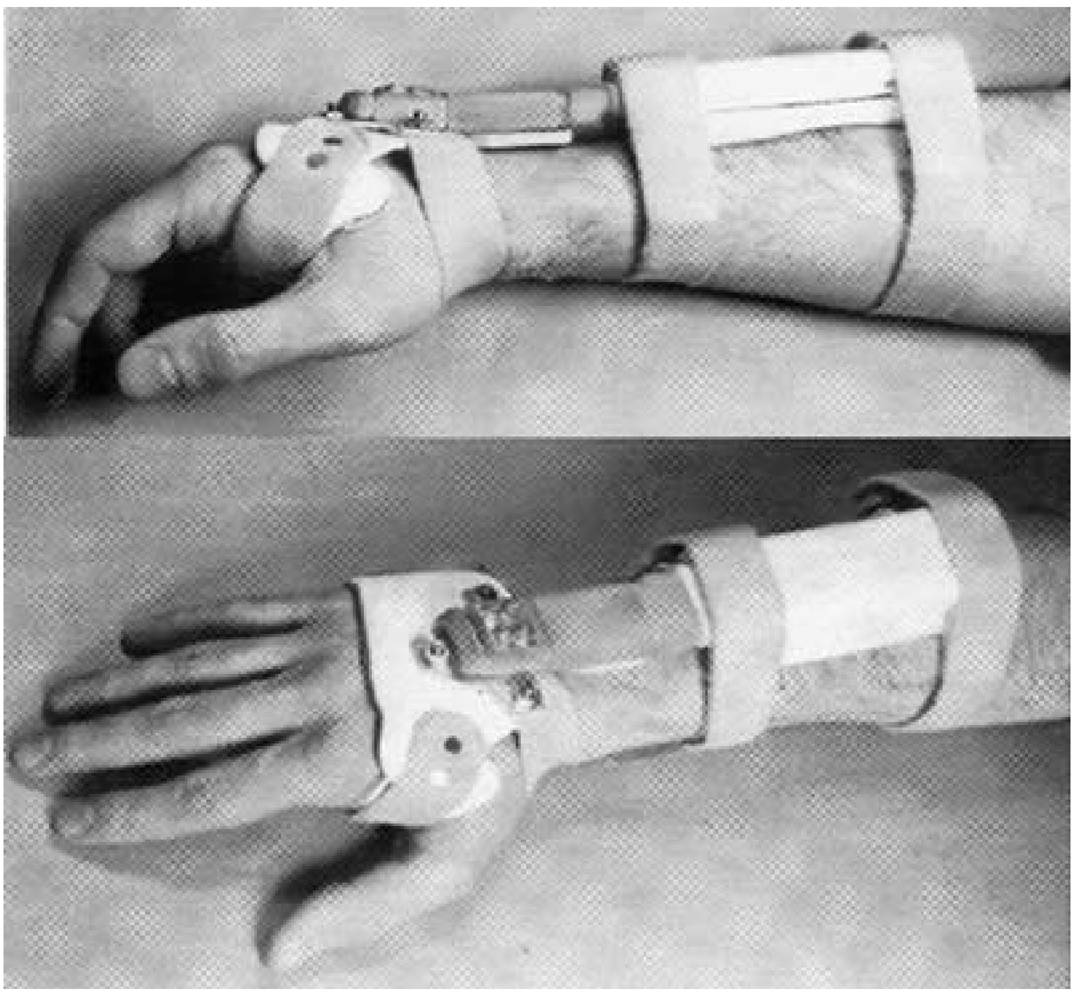


Figure 7. The Viscous Beam and cuff mounting system.

Both objective and subjective factors play a role in determining whether a person will find the orthosis sufficiently comfortable, convenient, and unobtrusive to wear on a regular basis. Psychologically, it is important that the orthosis not introduce unacceptable tradeoffs between tremor reduction and other determinants of its utility. Available DoFs with regard to size, weight, and shape should all be used to increase its likelihood of acceptance. These factors mitigated strongly in favor of the Viscous Beam design. Physically, the orthosis should not be irritating to wear and should not hinder intentional motion. Because the device must apply loads to skeletal structures through soft tissue layers, the skin's physical properties set a limit on the force coupling of the device to the arm. Specifically, comfort and the health of the skin depend on avoiding excessive abrasive loads, shear loads, and normal loads.

That this design imparts minimal shear stress to the skin may be seen as follows. The only requirement for the Beam to function as intended is that one end of the plate remain parallel to the back of the hand and the other end remain parallel to the forearm. This specification requires only that a moment be supported at each end to maintain the necessary angular alignment. The two force couples required to produce these moments are all normal to the skin.

The kinematics of the Viscous Beam also require that it be permitted to slide axially relative to the forearm cuff only. The current design of the forearm cuff includes a teflon-lined pocket in which the teflon-covered-beam (exterior to the latex covering) slides. This constraint supports the force couple but allows the beam to slide axially along the forearm. The teflon-teflon interface provides minimal resistance to the sliding motion and therefore introduces little shear between the forearm cuff and the skin.

The moment at the back of the hand is more difficult to support than the moment on the forearm, because the hand's size constrains the axial length of the cuff. Since a greater distance between the two forces in the required couple allows those forces to be smaller, the proximal-distal dimension of the cuff should be maximized to minimize the resulting pressures on the hand (a tradeoff of increased cuff size for increased comfort). In the prototype, the Beam is fastened to the hand cuff via an aluminum stiffener.

The current prototype (shown in **Figure 7**) does not permit ulnar and radial deviation of the wrist, except through compliance of the cuff system. To eliminate this constraint, the cuffs would need to allow rotation of the beam's ends about axes normal to the cuff surfaces, an additional complexity not attempted in the development of the prototype reported here.

It is important that both cuffs used to mount the Beam be made with a custom fit to the individual wearer. A loose fit would contribute backlash to the system, which diminishes the effectiveness of the damper. Further, cuffs that are too tight will impede circulation and be uncomfortable to wear. The cuffs should also be sufficiently stiff to support the force couples associated with use; compliance in the cuffs would contribute to backlash in the system and to localized pressures on the wearer's skin. The cuffs used for the prototype were made from Multiform I splinting material (Alimed, Dedham MA). This plastic may be repeatedly heated to permit iterative molding to the hand. An adhesive-backed, 3 mm, closed-cell foam is used as a liner to help distribute the loads of the damper so that the cuff is more comfortable to wear. The cost of this comfort is added compliance in the system. The cuff-mounting system may be custom fitted to a user in about 20 min by a physical or occupational therapist; the expertise of an orthotist is not required.

Elastic hook-and-loop strapping is used to attach the cuffs to the hand and arm. The use of elastic strapping allows the damper to be firmly held to the hand. The strap that passes proximally around the thumb is important in helping to support the moments of the Beam. The flexible strap used for this purpose does not inhibit the motion of the thumb or the wrist.

The device could be fabricated in many colors by using colored fabrication materials to suit the preferences of the user. The completed device is durable in construction and easy to clean with soapy water.

DISCUSSION

As a tremor-suppression orthosis, the prototype Viscous Beam succeeds in varying degrees in meeting the design goals:

1. The Viscous Beam damps wrist flexion and extension tremor. Characterization of the device shows damping levels achieved by the device are lower than anticipated, due to reduced functional fluid viscosities.
2. The elastic stiffness of the system is small and does not impede intended wrist flexion and extension; stiffness loads are less than 15 percent of the intended damping load of the 4× damper for severe tremor motions.
3. The device is safe to use and does not appear to risk harming the user in any way that can be anticipated prior to full activities-of-daily-living tests.
4. The arm-mounting cuffs are comfortable to wear and were designed to minimize contact stress localization on the skin. Ventilation of the arm and hand cuffs exceeds that of most commercially available orthoses worn on the lower arm and hand, in that more skin is exposed.
5. The Viscous Beam is very compact, relative to alternative designs. The forearm-mounted components will fit within a shirt sleeve, and the hand component is small enough to fit in a normal glove if desired. The low-profile shear-plate damper and bending plate transmission were designed expressly to not impede normal interaction with the environment.
6. The Viscous Beam is capable of bending through an angle exceeding that of wrist flexion-extension, thereby setting no limit on the range of motion of the hand in this DoF. The cuffs were designed to not hinder pronation and supination of the forearm, although the current cuff system does hinder ab/adduction of the wrist.
7. The Viscous Beam requires no external regulation or control. Some users will be able to don and doff it independently, while others will need assistance. This is not out of keeping with other successful assistive technology. Its operation and appearance are extremely simple, incorporating no adjustments and no observable relative motion of parts.
8. Based on the costs of orthoses of similar mechanical complexity, it appears that the Viscous Beam could be produced at costs the market will bear. Products of a similar category (not necessarily related to tremor control) that bracket the mechanical complexity of the Viscous Beam include: the Jaeco Friction Controlled Arm Positioner (passive, mobile arm support) priced at $175 (Jaeco Orthopedic Specialties, Hot Springs, AR); an adjustable leg orthosis for training, costing between $700 and $900; continuous

passive motion devices for upper limb therapy costing approximately $2500.

Based on this market calibration and on the Viscous Beam's size and the functionality it provides, it should be marketed for $400-600. Considering the material and labor costs likely to be required to fabricate the Viscous Beam, it could in fact be brought to market for this price.

Preliminary clinical trials have been conducted to quantify the device's ability to reduce tremor and qualitatively assess its ease of use. Results from these and continued studies will be presented in future publications. A brief summary of evaluation to date is as follows: Preliminary quantitative trials show that the Viscous Beam is able to reduce tremor and improve control for all of the five subjects tested. Of the three subjects with isolated wrist tremor, qualitative testing shows greatly improved performance in writing tasks and water pouring tasks for two of the subjects. Testing with controls and subjects with tremor demonstrate that users with mild tremor or no active tremor are able to don the device independently. Users with more severe tremor require assistance from an aide in donning the device. The device may be doffed by all subjects independently (with some difficulty by those with severe tremor).

The device is intended for daily use as needed. It may be worn for specific activities, such as eating a meal, or used throughout the day as the user prefers. Long-term clinical trials to be conducted will provide insight into its likely use.

As part of the development of the Viscous Beam, a literature search was conducted to determine whether similar configurations have been conceived and applied elsewhere. Several related concepts were found, although none were designed or are being used to perform the same function as the Viscous Beam and none share its range of motion. All of the devices include a solid (except for the electro-rheological beam discussed below) viscoelastic laminate layer in a structural composite to achieve what is termed constrained layer damping (CLD).

CLD provides an effective and important means for damping structural vibrations and noise in a large variety of applications (35-39). The traditional role played by constrained layers has been to force the viscoelastic layer to deform in shear rather than extension, thereby increasing strain in the viscoelastic layer and with it energy dissipation (40,41). CLD can only function under very small deflections (e.g., very large bending radii) because the composite layers cannot slip relative to one another and, more importantly, the thickness of the elastomeric layer changes with small bending radii. For this reason, CLD is confined to a small class of applications. Because the Viscous Beam can bend to a radius of curvature as small as 2.5 cm and could be designed to bend to smaller radii, it is useful in a much broader range of applications. Additionally, the ratio of damping to stiffness possible with the Beam far exceeds typical CLD applications. This fact makes it particularly well suited to a tremor suppression orthosis and other damping applications where elastic return is not desired. In fact, the Viscous Beam could be used to replace viscoelastic CLD devices in a number of applications where lower stiffness is desirable.

CLD is also implemented in an active form that permits electrically tunable damping. Several groups have produced piezoelectric or electro-rheological (ER) CLD devices the damping properties of which may be controlled with an applied voltage (42-45). As with passive CLD, active CLD could not be used for a tremor-suppression orthosis due to its high stiffness and inability to accommodate large angular deflections through a small bending radius. Additionally, the power demands of these systems, the non-Newtonian behavior of the ER devices, and the coupled stiffness change with damping change would be an unacceptable basis for a tremor-suppression orthosis.

Despite the differences in implementation noted above, the Viscous Beam may be classified as a CLD device and achieves damping in a fashion similar to the other CLD devices described. It is, however, unique in that it delivers resistance through much larger deflections with much lower elastic stiffness. It is able to withstand 180° deflections through a radius of curvature of 2.5 cm. At the frequencies of interest, the 4× prototype demonstrates a peak velocity-dependent resistance 2.7 times the peak elastic resistance (for full range of motion), substantially greater than the value noted above for other CLDs. Additionally, the highly compact Viscous Beam maintains a linear transformation of rotational motion to translational motion even for large deflections. This characteristic further differentiates this design from other technologies.

CONCLUSIONS

The Viscous Beam is a compact passive visco-elastic element that functions in bending to damp high-frequency tremor motion. Applied to the wrist, the prototype orthosis permits a normal range of intentional motion while applying a viscous load that has been shown in related work to selectively attenuate undesired tremor motion. The design incorporates, with no additional components, a novel transmission which linearly transforms the angular velocity of the wrist to rectilinear velocity of a flat-plate damper. The integral transmission and damper form a highly compact and unobtrusive system with an aspect ratio similar to the limb on which it is worn. This design is the only wearable damped wrist orthosis presently documented in the clinical or research literature.

The system was proven to produce the desired kinematics and meets the design goals except for nonlinearities caused from non-Newtonian behavior of the damping fluid. Although these nonlinearities resulted in a significant discrepancy between predicted and experimental damping response, the discrepancy in damping magnitude may be compensated for by modifications to the system geometry or choice of fluid viscosity.

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