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Methods for reducing energy dissipation in cosmetic gloves

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Abstract—For cosmetic reasons, hand prostheses are provided with cosmetic gloves. Their pleasing appearance, however, is accompanied by poor mechanical behavior, resulting in a negative influence on prosthesis operation. Glove stiffness is high and nonlinear, and internal friction in the glove material causes energy dissipation (hysteresis). In this article, two methods for reducing hysteresis in cosmetic gloves are proposed, that may be applied independently or in combination.

Glove modification. Altering the mechanical properties of the glove itself is the first method that is presented. It was found possible to reduce both stiffness and hysteresis about 50% by forming grooves into the inside of the glove. Together with the evaluation of this method, several properties of the cosmetic glove were determined.

Motion optimization. Additionally, a second method for reducing hysteresis was developed. The amount of hysteresis is influenced by the way the glove is forced to deform. The prosthesis mechanism, determining this deformation, was designed for minimum hysteresis and maximum cosmesis. For the prosthesis-glove combination used in this study, thumb motion optimization reduced hysteresis by about 65%.

Key words: *compensation mechanism, cosmesis, cosmetic glove, hand prosthesis, hysteresis, material properties, PVC, viscoelasticity.*

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INTRODUCTION

A small group of mechanical engineers, within the section of Man-Machine-Systems at Delft University of Technology, form the WILMER Group. They have specialized in the development of hand prostheses for about 20 years now. In the opinion of the Group, a good prosthesis should not only perform motoric functions in a fast, silent, and reliable manner, but should also fulfill three basic demands: pleasing cosmesis, high wearing comfort, and easy controllability, generally in this order of priority (1,2).

For hand prostheses, inconspicuous appearance is established by using cosmetic gloves. Unfortunately, the glove has a negative influence on the fulfillment of the other demands because of its poor mechanical qualities. In simple body-powered prostheses, high glove stiffness in combination with normal operating strokes leads to considerable, thus uncomfortable, operating effort. It is one of the reasons why designers tend to apply servo-systems, as in myoelectric hand prostheses. However, by doing so, one of the main qualities of body-powered devices is lost, as no tactile or proprioceptive feedback of opening width and pinching force exists in customary servo-controlled prostheses (2). As proper feedback is essential for the controllability of any system (3), it is worth trying to reduce operating effort in a different way. Reduced glove counteraction will benefit all types of hand prostheses that go with cosmetic gloves.

From a mechanical point of view, the glove is a source of major problems for the users of hand prostheses in daily activity, and for designers to solve. Elimination of the glove is not appropriate, as there are many users who judge a hand-like prosthesis without a

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glove to be cosmetically unacceptable. The problems are a result of the fact that cosmetic coverings are made of viscoelastic materials (those that possess both elastic and viscous properties). The deformation energy of an *elastic* body is a function of displacement, while in *viscous* media, deformation energy is a function of velocity. If an object made of viscoelastic material is deformed periodically, some of the energy input is stored and recovered in each cycle—elasticity, and some is dissipated—viscosity (4,5). The viscous behavior and the elastic behavior of the glove will be discussed separately, after an introduction of the terminology used in this paper.

Terminology

Materials constants are independent of the geometry of a body or the deformations imposed on it, contrary to *properties* of bodies. In this paper, two methods will be proposed to improve several *properties* of cosmetic gloves. The term *hysteresis* will be used for the energy dissipation in one operating cycle, and is, therefore, expressed in the unit of mechanical energy: Nm. In cyclic phenomena, the force-displacement curves of forward and reverse motion (or deformation) are not identical as a result of this energy dissipation. The enclosed area of both curves, expressed in Nm, equals the amount of hysteresis. The term *stiffness* is defined as the derivative (i.e., the slope of the curve) in each point of the force-displacement function for translational stiffness (or the moment-rotation function for rotational stiffness). Therefore, translational stiffness, as in tensile tests where force and displacement are measured, is expressed in N/m, while rotational stiffness has the unit Nm (or Nm/rad). In *linear* elastic material, strain ϵ [%] (or relative deflection, i.e., the ratio of deflection Δl [m] and initial length l [m]) is proportional to stress σ [N/m^2] according to Hooke's law: $\sigma = E \cdot \epsilon$, in which E [N/m^2] is the materials constant called Young's modulus. As stress is the ratio of force F [N] and area A [m^2], the translational stiffness c [N/m], defined as the ratio of force and deflection, is found as EA/l, and is, therefore, dependent on geometry, but not dependent on strain. Young's modulus of materials that do not follow Hooke's law (e.g., viscoelastic materials) is not constant: their stiffness is dependent on strain and is called *nonlinear*.

Elastic Behavior

In **Figure 1,** the characteristics of three PVC gloves (Otto Bock, size 12) are displayed. The figure gives the relation between the thumb angle ϕ (0 radians correspond to a closed position, 0.6 radians to fully opened) and the required operating moment T [Nm]. Elasticity is recognized in the increasing moment that is required for increasing angles. Contrary to technical springs, having constant stiffness at all deflections, the nonlinear elastic material properties of the glove, complicated by its three dimensional (3-D) shape, result in a highly nonlinear progressive stiffness (i.e., the slopes of the curves increase as a function of deflection).

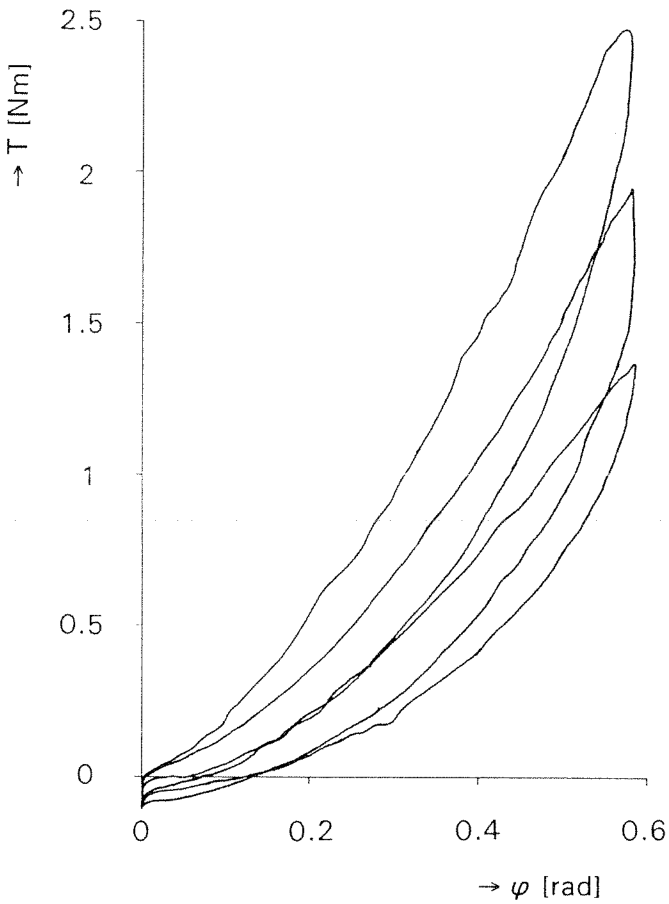

Figure 1.
The nonlinear relationship between operating moment and thumb opening angle for three different size 12 Otto Bock gloves in combination with the WILMER ultra lightweight hand prosthesis. The slope of the curves is a measure for the stiffness. The area enclosed by the opening and closing curves of one cycle is a measure for the amount of hysteresis.

In principle, the influence of stiffness can be overcome by adding a compensation device to the prosthesis (6–8). This is a spring mechanism that balances the elastic glove force throughout the whole range of motion. The compensation device delivers the force and the energy required to open the prosthesis against the action of the glove, and stores the energy that is released by the glove when the prosthesis closes again. Perfect compensation would thus cancel the need for operating energy during free movement of the prosthesis: the elastic influence of the glove on prosthesis operation would be fully eliminated, as if there were no glove present. However, practical applications are impeded by the extremely nonlinear glove force characteristic. An additional complication is that the glove-to-glove stiffness varies by as much as a factor two over a product series (**Figure 1**). For this reason, the compensation mechanism must be made adjustable. Nevertheless, present conventional compensation devices are capable of decreasing operating energy by 40 to 60 percent (6,9).

Viscous Behavior

As can be seen in **Figure 1,** the opening and closing curves of an operating cycle are not identical, a phenomenon that is called hysteresis. Due to internal friction, movement through or deformation of a viscous medium requires force, but this force is nonconservative and thus the process is not reversible: energy is dissipated. The enclosed area of the curves in **Figure 1** is a measure of the energy dissipated during one cycle of prosthesis motion. For most gloves in normal operation, approximately one third of the input energy is dissipated by deformation of the glove (6). As hysteresis, contrary to stiffness, cannot be compensated for without devices that require external operating energy, hysteresis should be minimized prior to the design of a compensation device, if a prosthesis with low operating energy is to result. This study addresses the problem of reducing hysteresis.

METHODS

For a given deformation trajectory, the amount of hysteresis is influenced by the mechanical properties of the deformed object. For an object with given mechanical properties, the course of its deformation path, to reach a certain position, influences the amount of hysteresis: the amount of elastic energy stored is only dependent on the final position, but viscous energy is dissipated along the whole trajectory.

Therefore, hysteresis can be reduced in two ways: the mechanical properties of the glove itself may be modified, or the prosthesis mechanism may be altered, so that the glove deforms differently, causing less hysteresis losses. These two methods, glove modification and motion optimization, are described below.

Glove Modification

Improving the properties of the glove by using different materials without losing other important qualities is far from easy (10–14). However, the mechanical properties of the glove can also be modified by changing its geometry, rather than selecting different material. In previous research carried out by the WILMER group, a 50 percent reduction of both hysteresis and stiffness was found to be possible (6). This was achieved by removing material from the inside of the glove in the region between thumb and fingers where the glove is forced to stretch most. Unfortunately, the method used was not reproducible, because the modification was carried out by hand.

To overcome this problem, an alternative modification method is proposed, called the heat-wire treatment. With no moving elements, the setup is simple (**Figure 2**). The glove is pressed against electrical resistance wires (Kanthal, 1.81 Ω/m, 1 mm diameter) fixed on a mold that fits exactly in the glove. By electrically heating the wires (with 6.5 A current), a series of grooves is formed in the inside surface of the glove (**Figure 3**). The outer surface of the glove remains unharmed, and the grooves are hardly visible from the outside.

Prior to its application to gloves, the heat-wire treatment was tested upon rectangular specimens of glove material, cut from unused cuffs of Otto Bock gloves. To evaluate its effects on glove material properties, specimens were investigated by using a computer-controlled tensile testing machine. The width of the specimens was 25 mm, their length 45 mm, while their thickness, determined by the gloves, varied from 1.1 mm to 1.6 mm. Clamped over their full width in specially made grippers of the tensile testing machine, the effective length of the specimens was 17.3 mm. The grooves, if present, were arranged perpendicularly to the stretching direction, and were distributed uniformly along the effective length.

Several tests were carried out with the specimens. The main interest was in the reduction of hysteresis by the heat-wire treatment. For that purpose, each individual specimen was tested both before and after modification. A complication is that some properties of viscoelastic materials assume stable values only after a

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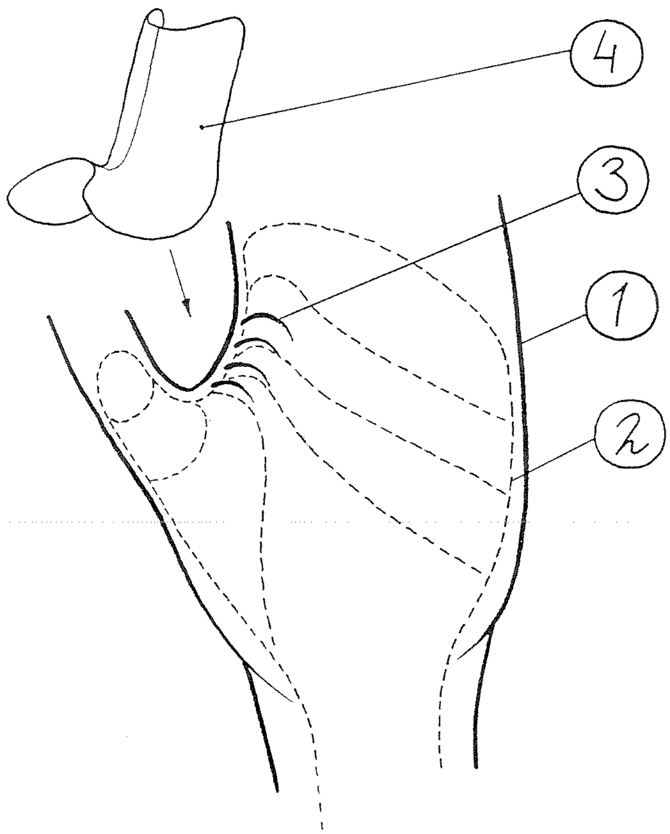

Figure 2.
Heat-wire treatment setup. Electrical resistance wires are placed in the region where the glove is forced to stretch most. 1=glove, 2=internal mold, 3=heat wires, 4=external mold.

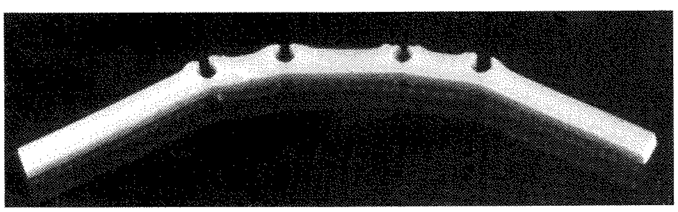

Figure 3.
Section of the glove, perpendicular to the grooves. No material is removed, but the glove section is reshaped.

number of cycles, a phenomenon called conditioning. To investigate this for glove material, a series of four tensile tests was performed upon an individual specimen, one directly after the other. For each of four specimens, this procedure was executed before modification, after modification with four grooves, and after double modification (i.e., with eight grooves). Other tests were performed to assess the influence of stretching velocity and the extent of stretching. Unless otherwise indicated, all tensile tests were executed upon modified specimens (four grooves), with maximum strain of 30 percent (fairly normal in hand prostheses with cosmetic gloves) and cross-head velocity of 0.1 mm/s. Finally, the heat-wire treatment was tested on complete gloves, and a fatigue test was performed to assess the lifetime of the modified glove.

Motion Optimization

In contrast with elastic forces, viscous forces are nonconservative. Viscous energy is thus dependent on trajectory. Therefore, a second possible reduction method is to optimize prosthesis motion with minimum hysteresis as the criterion. An additional demand is that a certain opening width of the hand should be achieved in a natural way, so that the glove does not fold or crease.

For finding the optimum, a test setup is required that enables the prosthesis to perform different motion cycles reproducibly, while force and displacement must be measured in order to calculate hysteresis. On the other hand, the search for cosmetic movements requires a test setup with a great freedom of movement, in the sense that several sorts of movement can be carried out. To avoid the complex testing equipment necessitated by these competing requirements, the process was divided into a *cosmesis phase* and a *hysteresis phase,* each using a simple test setup. With the first setup, the limited field of cosmetic motions was assessed by performing a great variety of prosthesis motions and selecting the cosmetic ones (cosmesis phase). The second setup was used to measure force and displacement of different motions within the cosmetic field only, in order to assess the minimum hysteresis motion (hysteresis phase). The result after both phases, a cosmetic motion with minimum hysteresis, will be called the optimal motion.

Materials

For all the experiments in method 2, the WILMER ultra lightweight hand prosthesis was used (15), in combination with a size 12 Otto Bock glove. The glove was not modified by the heat-wire treatment. As only the thumb of this prosthesis can move, the problem of prosthesis motion optimization reduces to finding the optimal thumb motion. However, the methods described are also applicable to other types of prostheses. The procedures of the two phases are described below.

Cosmesis Phase

Attractive hand movement depends on the motion of the fingers relative to the palm, on the shapes of the fingers and the palm, and on the glove's fold and crease behavior. In the cosmesis phase, the thumb of the test prosthesis was moved through space by using the experimental setup shown in **Figure 4.** The mechanism for actuating the prosthesis, as well as the thumb pivot, was removed, so that the thumb movement was not prescribed and only hampered by the glove. With an L-shaped bar attached to its end, the thumb was led through a series of cosmetic positions, until an opening width of 40 mm was reached. With the thumb held in each cosmetic position, the spatial coordinates of the bar were measured using the palpator (16), which automatically calculates and stores the position of the thumb. With this setup, the cosmetic field, consisting of all cosmetically acceptable thumb positions, was determined.

Hysteresis Phase

In order to find the movement with minimum hysteresis, more than 50 slightly different motions within the cosmetic field were evaluated with a specially made apparatus (schematic layout **Figure 5**, photograph **Figure 6**). The same test prosthesis was used again, its thumb now attached to an externally mounted driving axis, thus being forced to describe a cosmetic motion. The driving axis was driven by the computer-controlled tensile testing machine (not shown) that also calculates the amount of hysteresis. The motion of the thumb was easily adjusted by varying the positions of the two ball bearings of the external driving axis.

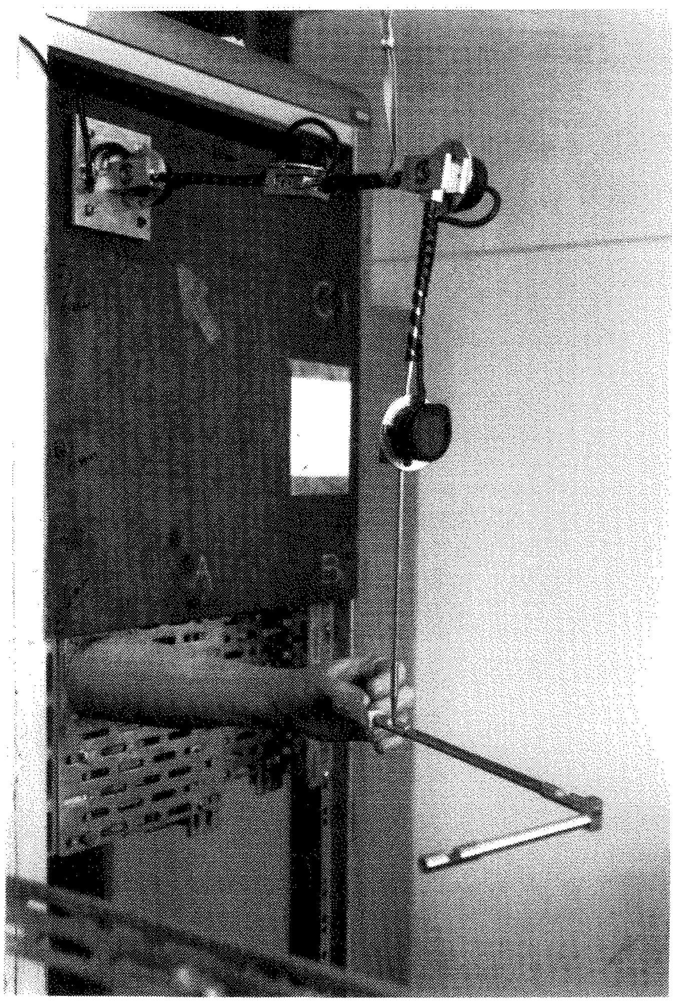

Figure 4.
Photograph of the experimental setup for the determination of cosmetically acceptable thumb motions. The thumb is moved by the bar attached to the thumb, while cosmetic positions are measured by the palpator, a 3-D position measurement device (16).

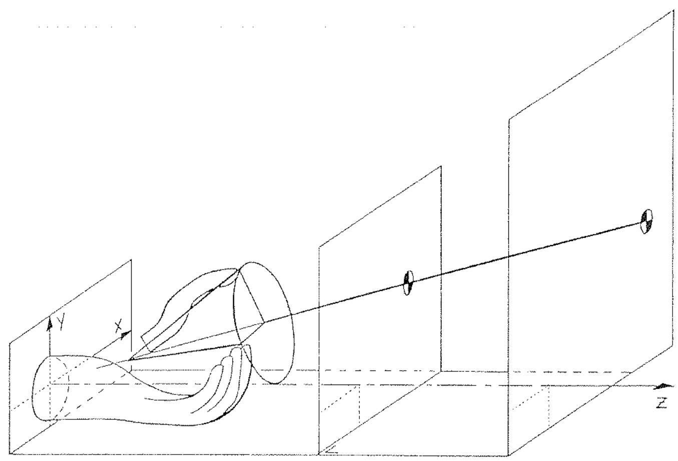

Figure 5.
Schematic view of the experimental setup for the thumb movement optimization. The cone that is described by the thumb is clearly visible. The externally mounted driving axis is hinged by two bearings, marked with ⊕.

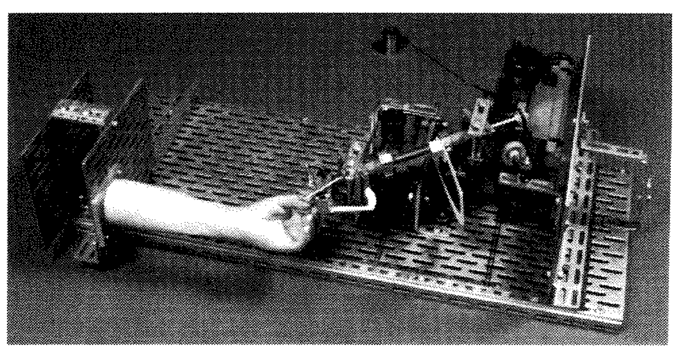

Figure 6.
Photograph of the experimental setup for the thumb movement optimization experiments. The tensile testing machine that is driving the axis is not shown.

RESULTS

Results of Glove Modification

This section will present the results of the heat-wire treatment applied to the rectangular specimens of glove material, some mechanical properties of the specimens before and after modification, and the first results of the glove modification outcome. As a result of viscoelasticity, the mechanical properties are dependent on strain, strain rate, and testing history. The scatter in the data, indicated by error-bars in the graphs, is a result of this variance, not of measurement inaccuracy. As the specimens' stiffness is not constant, a representative value of the nonlinear stiffness encountered in each tensile test is displayed in the graphs. The ratio of final force and total deflection (i.e., the average stiffness) is used as this value.

Conditioning

In **Figure 7,** results are presented of a series of four tensile tests, executed upon one specimen, one directly after the other. Each graph shows the conditioning curves of specimens with zero, four, and eight grooves. The graphs show the average data and the deviation limits for a population of four individual specimens. Hysteresis (**Figure 7a**) sharply reduces after the first cycle, and remains rather constant thereafter. In cosmetic gloves, this unpleasant behavior cannot be compensated for without complex devices. For stiffness (**Figure 7b**), conditioning is far less distinct, which is fortunate with respect to the design of compensation devices, because only one of the cycles (i.e., the first cycle or the subsequent cycles) can be compensated exactly if devices using external energy are to be avoided. From the graphs it can also be seen that both hysteresis and stiffness of specimens of modified glove material are only about half the values of specimens of virgin material, which demonstrates that the proposed heat wire treatment performs as well as the earlier mentioned manual glove modification methods (6).

Strain Rate

The strain rate (i.e., cross-head speed divided by initial length, in percent per second) also affects the operation of the prosthesis. **Figure 8a** shows the relationship between stiffness and cross-head velocity for specimens of modified glove material. In the range from low to normal prosthesis operating velocity, stiffness is raised by 50 percent, approximately. Apart from being unpleasant for prosthesis users, this is a problem for the designer of a compensation device: since the operating speed is unknown in the design stage, the stiffness for which to compensate must be estimated. Hysteresis is even more strongly dependent on cross-head velocity, in a nonlinear way, as is shown in **Figure 8b.** The curve possesses a minimum at a velocity of 0.5 mm/s approximately.

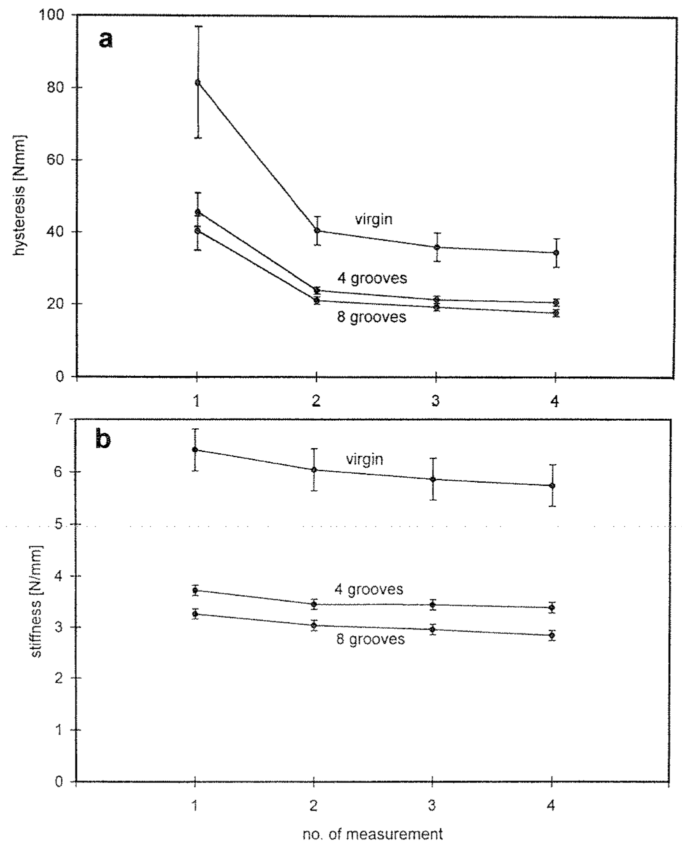

Figure 7.
a) hysteresis of specimens of glove material suffers strongly from conditioning. b) stiffness of specimens of glove material is not much influenced by their deformation history.

Strain

The extent to which the glove material is stretched (i.e., the maximum strain) also influences its behavior. The average stiffness is not constant, but increases gradually with increasing maximum strains (see **Figure 8c**). Hysteresis is also strain-dependent, according to the nonlinear relationship shown in **Figure 8d.**

Glove Modification

The above results all concern rectangular specimens of glove material. During the project, there was no

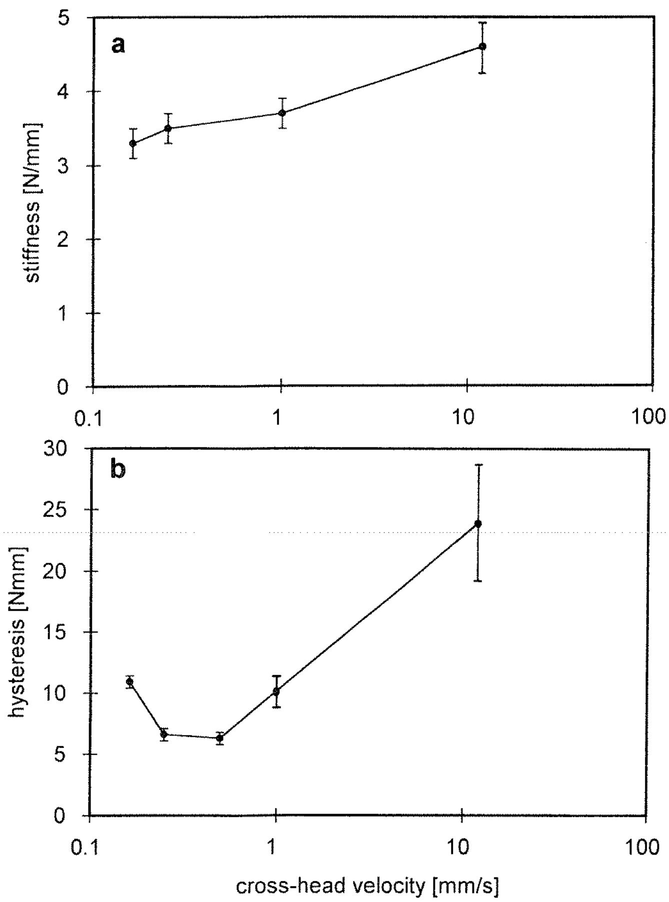

Figure 8a,b.
a) dependence of stiffness on speed of movement for specimens of modified glove material. Stiffness increases gradually with increasing velocity. b) dependence of hysteresis on speed of movement for specimens of modified glove material. The curve possesses a minimum at a velocity of 0.5 mm/s approximately.

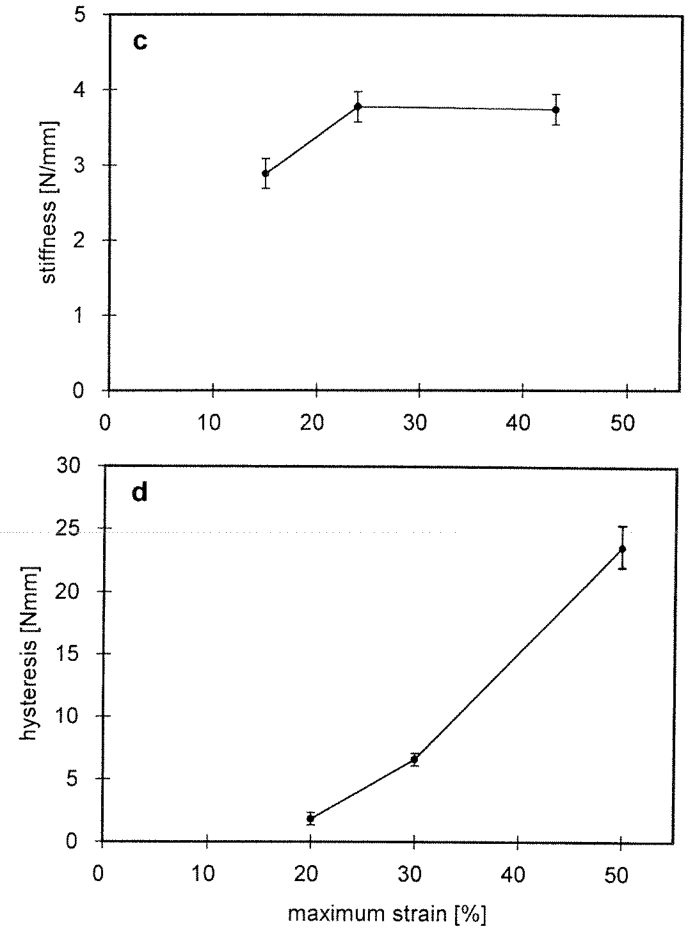

Figure 8c,d.
c) dependence of stiffness on maximum strain for specimens of modified glove material. Stiffness is fairly constant, except for low strains. d) dependence of hysteresis on maximum strain for specimens of modified glove material. Hysteresis increases progressively with increasing strain.

opportunity to perform extensive research with a 3-D version of the heat-wire treatment apparatus according to **Figure 2** for the modification of gloves. However, several exploratory tests were carried out. Because of its 3-D shape, pressing the glove uniformly against the heat-wire mold presented problems. Nevertheless, a hysteresis reduction of approximately 30 percent was attained.

Fatigue Test

A fatigue test has been carried out to evaluate the lifetime of the modified glove. The glove was still intact after 20,000 cycles, which is considered to be sufficient (17). The mechanical behavior is considered representative for the characteristics during the glove's lifetime (14).

Results of Motion Optimization

In the cosmesis phase, the freely moving thumb was led through several series of cosmetic positions. It was found that, apart from the palmar and lateral grip, a movement in which the thumb follows a curve is possible, which looks very natural (**Figure 9**). Kinematic analysis showed that this motion can be approximated by a cone motion (i.e., the thumb moves along the surface of an imaginary cone). Because of its cosmetic effect and apparently low counteraction, this cone motion was chosen to be optimized in the hysteresis phase.

In the hysteresis phase, the minimum hysteresis cone motion was assessed. In **Figure 10,** the hysteresis

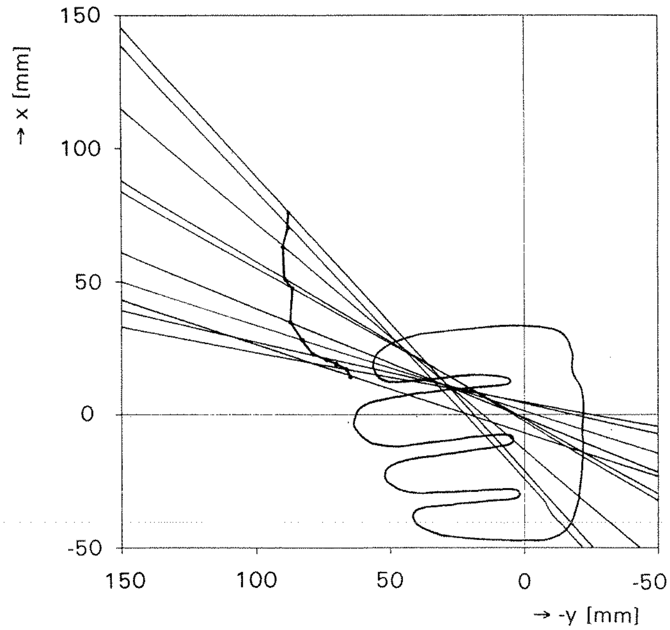

Figure 9.
Proximal view of test prosthesis with bent fingers, showing the cosmetic thumb movement that can be approximated by a cone motion. The trajectory of the tip of the thumb and center lines of the corresponding thumb positions are shown.

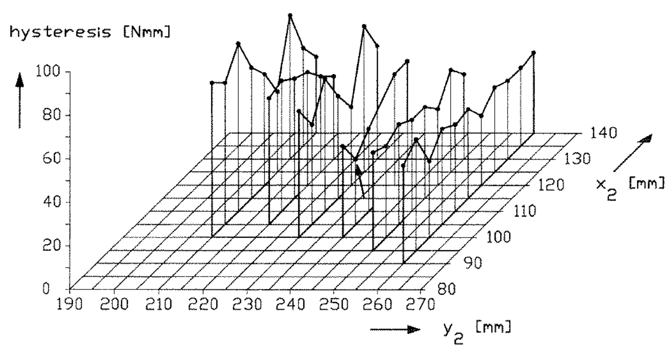

Figure 10.
Graph of hysteresis as a function of cone motion driving axis orientation. The position of bearing ⊕2 is used as a measure for the thumb axis orientation. The minimum is located at $(x_2,y_2)=(105, 240)$, its value is 32 Nmm. This position corresponds to a movement with uniform glove stretching.

of all investigated motions is presented as a function of the position of the second ball bearing, which proved to be a reliable measure for the orientation of the driving axis. Evidently, hysteresis is rather sensitive to variations of the orientation of the driving axis, but the dip at coordinates $(x_2y_2) = (105, 240)$, indicating the optimal motion, is clearly visible. Its hysteresis value, 32 Nmm, is remarkably low: approximately one-third of the original prosthesis (15), which was designed with only cosmesis as a criterion. As a side effect, stiffness was reduced by approximately 45 percent. Apart from the mechanical advantages, the optimal motion is one of the most pleasing movements within the cosmetic field, thanks to its very uniform glove deformation.

DISCUSSION

Cosmetic gloves with an inconspicuous appearance are desirable for hand prostheses. Therefore, their negative influence on prosthesis operation should be minimized. Viscoelasticity makes the characteristic of a glove strongly dependent on sequence, strain, strain rate, opening movement (and time and temperature among the noninvestigated variables), and induces stiffness and hysteresis. It was argued that the influence of stiffness can be eliminated by applying a compensation device, while hysteresis at best is minimized by altering the glove or the motion of the prosthesis' fingers. This observation lead to the proposition of two methods to minimize hysteresis: glove modification, and motion optimization.

Glove modification, by means of the heat-wire treatment, turned out to be an effective and reproducible method for reducing hysteresis in PVC cosmetic gloves. Both hysteresis and stiffness can be halved, and, in principle, the variation in stiffness between gloves can be reduced by varying electric current or process time. If the method for pressing gloves against the heat wires is improved, modification of gloves is expected to give the same results as modification of specimen strips. From the measurements presented, it can be concluded that a prosthesis mechanism should strain the glove as uniformly as possible. Low strain favors the design proportionally with respect to stiffness, and more than proportional when hysteresis is considered.

Optimizing thumb motion, for the WILMER ultra lightweight hand prosthesis in combination with a size 12 Otto Bock glove, shows a reduction of hysteresis by approximately a factor of three compared to the original motion, which was designed with cosmesis as a criterion. Thus, for an efficient hand prosthesis, the mechanism should not be designed with only cosmesis as the criterion; hysteresis must be considered as well. The optimal motion that was identified appeared to be highly cosmetic; thanks to the cone motion, it looks natural and the glove deformation during operation is very uniform, which partly explains the low counteraction.

Currently, the WILMER group is designing a hand prosthesis to operate with the optimal motion, including a compensation device to eliminate the remaining stiffness, aiming at an easy-to-operate body-powered hand prosthesis.

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