

A mechanism to compensate undesired stiffness in joints of prosthetic hands

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This is a post-refereeing version of an article whose final and definitive form has been published in the journal 'Prosthetics and Orthotics International', which can be found at: <http://dx.doi.org/10.1177/0309364613488620> (© SAGE Journals)

Abstract

Background: Cosmetic gloves that cover a prosthetic hand, have a parasitic positive stiffness that counteracts the flexion of a finger joint.

Objectives: Reducing the required input torque to move a finger of a prosthetic hand, by compensating the parasitic stiffness of the cosmetic glove.

Study Design: Experimental, test bench.

Methods: The parasitic positive stiffness and the required input torques of a PVC and a Silicone glove were measured when flexing a MCP finger joint 90°. To compensate this positive stiffness, an adjustable compensation mechanism with a negative stiffness was designed and built. A Matlab model was created to predict the optimal settings of the mechanism, based on the measured stiffness, in order to minimize the required input torque of the total system. The mechanism was tested in its optimal setting with an applied glove.

Results: The mechanism reduced the required input torque with 58 % for the PVC glove and with 52 % for the silicone glove. The total energy dissipation of the joint did not change significantly.

Conclusions: This study shows that the undesired positive stiffness in the joint, can be compensated with a relatively simple negative stiffness mechanism, which fits inside a finger of a standard cosmetic glove.

Clinical relevance

This study presents a mechanism that compensates the undesired stiffness of cosmetic gloves on prosthetic hands. As a result it requires less input force, torque and energy to move the fingers. Application of this mechanism in body-powered hands will reduce the control effort of the user.

Keywords

Upper limb prosthetics, cosmetic glove, compensation mechanism, prosthetic design

Background

The artificial hands used in the prosthetic field are usually covered by a cosmetic glove, made out of silicone or PVC.¹ The cosmetic glove gives the hand a more lifelike appearance and it protects the hand mechanism against water and dirt. Unfortunately the cosmetic glove has also some negative properties, especially from a mechanic point of view. The stiffness of the glove material counteracts the movement of the hand mechanism² and of the finger joints.³ As a result the operator has to deliver extra input energy to operate the prosthesis. This results in an increased user effort in body-powered prosthesis, which are directly operated by the user.^{4,5} It also results in a decreased battery life in electric-powered prostheses. These undesired effects can be reduced by lowering the glove stiffness.² Another solution is to counteract the parasitic glove stiffness, by using a stiffness compensation mechanism. Such a mechanism has a stiffness which is opposite to the parasitic stiffness of the glove.^{6,7} Although such a mechanism has been described in some papers,^{2,6,7} it has not been built and evaluated. The myoelectric System Hands by Otto Bock do have some glove compensation, which is provided by a wire spring inside the palm of the hand. However this spring is only applied in the electric hands, not in the body-powered hands, and it compensates only one degree of freedom. It would be desirable to be able to compensate more degrees of freedom, in multiple joints.

Problem definition

The stiffness of the cosmetic glove causes an undesired joint torque in the finger joint of a prosthetic hand. As a result an extra input torque is required to move a finger joint.

Goal

The goal of this study was to design and evaluate a mechanism that compensates the undesired stiffness in finger joints of prosthetic hands, which is induced by the cosmetic glove. In this way the compensation mechanism should reduce the input torque that is required to move a finger joint.

Methods

The positive parasitic stiffness of the cosmetic glove can be compensated by a spring with a negative stiffness (Figure 1). Figure 1a shows the force-displacement curve of a typical positive stiffness linear spring. When such a spring is elongated (displacement on the x-axis increases) the spring pull force increases linearly (the force on the y-axis increases). The curve has a positive slope. In order to enable a forceless motion, the positive stiffness spring needs to be compensated. This can be achieved by using a spring which has exactly the same behaviour in the opposite direction. Instead of an increasing pull force, such an 'imaginary spring' would need to deliver a linearly increasing push force when the spring is elongated. As this force acts in the opposite direction, the force of this spring is considered to be negative. The force-displacement curve of such a negative linear stiffness spring is shown in Figure 1b. This curve is the exact reflection of the positive stiffness curve (Figure 1a), with respect to the x-axis. The curve has a negative slope, which means that the stiffness of the spring is negative. When both graphs are added, (i.e. the ends of both springs are attached together) the resultant curve is a line which runs along the x-axis, with a value of 0 (Figure 1c). In this way the sum of the spring forces of both springs is zero for every position. Therefore the moving point can be moved to every position, without any force. The slope of the curve is zero, which means that such a mechanism has a stiffness which is zero.

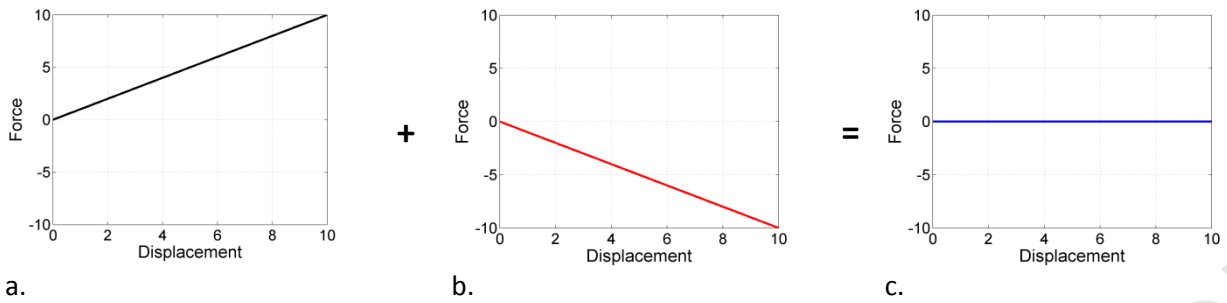


Figure 1, An undesired positive stiffness of a component (left) can be compensated by using a mechanism with a negative stiffness (middle). The result is a mechanism which can move with a zero stiffness.

Although there exists no spring with a negative stiffness, it is possible to create a negative stiffness by using a tension spring with a positive stiffness, together with two bars and three joints (Figure 2). When angle α increases the spring moves away from the joint axis and the moment arm increases. At the same time the spring shortens, which results in a decreasing force in the tension spring. The moment in the joint (M_{spring}) is the product of the moment arm and the spring force. It is possible to choose the parameters, e.g. spring stiffness, spring dimensions, and spring configuration, in such a way that the joint moment decreases when the angle displacement increases. In this way the slope of the resulting curve will be negative, which means that such a mechanism has a negative stiffness.

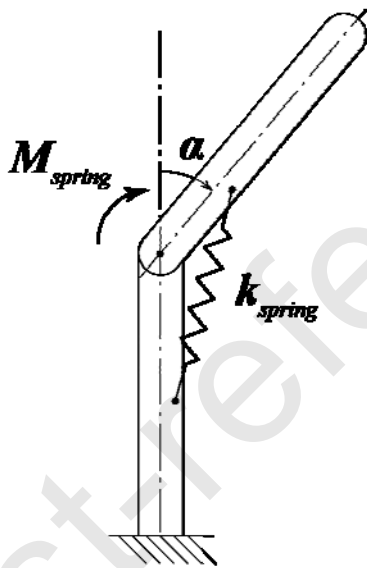


Figure 2 Schematic example of a negative stiffness spring mechanism. A tension spring with stiffness k_{spring} , exerts a torque M_{spring} to the upper bar. When the right spring parameters have been selected, the joint torque decreases, as the joint angle α increases.

Protocol

To compensate the parasitic glove stiffness in a finger's joint, the following steps were followed:

- The parasitic glove stiffness in the finger joint was measured, together with the required input torque and the energy dissipated by the glove. The glove was placed on the set-up and the finger was flexed from 0° to 90° and extended again.
- The measured force-displacement curve was fit with a linear approximation to approach the glove stiffness.
- The different feasible configurations of the compensation mechanism were modelled.
- The optimal solution was selected.
- The selected solution was implemented.
- The resultant stiffness in the finger joint was measured.

Test set up

A finger frame was placed inside the finger joint, to measure the joint stiffness (Figure 3). In this study the MCP-joint of the index finger was used. The finger frame consisted of two bars, connected with a joint. The joint had ball bearings, to minimize the joint friction in the finger frame. A cable running over a pulley controlled the joint angle. One end of the cable was attached to the measurement set up. The measurement set up activated the cable and measured the cable force and displacement. The other end of the cable was attached to a counter mass, which returned the finger joint to its initial position. The thumb of the glove was moved sideways out of the trajectory of the index finger, to avoid collision. The extension force applied by the counter mass was subtracted from the cable force. The resulting force, or activation force, was multiplied by the pulley radius to obtain the activation torque, which was recorded for every joint angle.

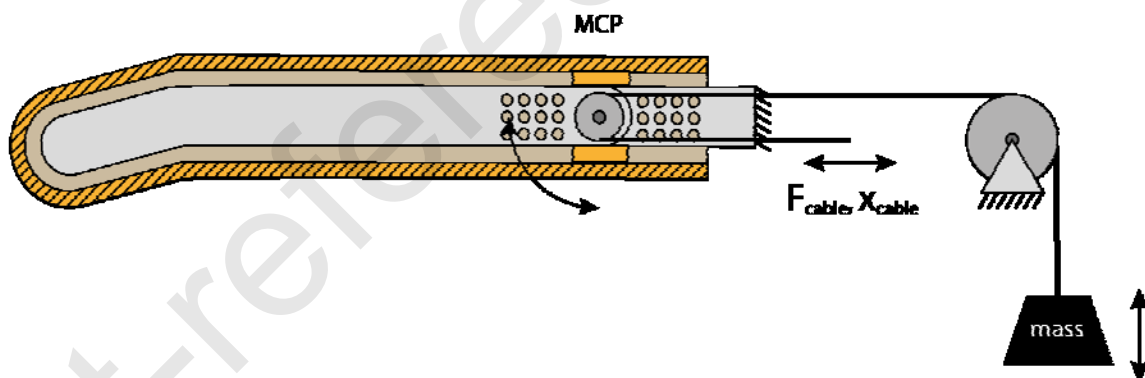


Figure 3 Test set-up to measure the joint stiffness. The finger was flexed by pulling the cable. The cable force and displacement were recorded. The counter mass extended the finger when the cable was released. The extension force applied by the counter mass was subtracted from the cable force. The mechanism was also used as a stiffness compensation mechanism, by placing two pins in the holes at the left and right side of the joint and by attaching a spring to those pins (see Figure 5).

Gloves

For the test two different cosmetic gloves were used, a silicone cosmetic glove (type: SG302/E4) and a PVC cosmetic glove (type: CG302/E4). Both gloves were manufactured by RSLSteeper (Figure 4) and had identical shape and size.



Figure 4 The RSLSteeper cosmetic gloves that were used in this study, the PVC glove (left) and the silicone glove (right).

Compensation mechanism

The finger frame of the test set-up was used as a compensation mechanism by attaching a helical tension spring to the frame. Above the joint and below the joint there were twelve spring attachment points, in a grid of 3 by 4. This enabled $12 \times 12 = 144$ different configurations. The distance between the centres of the holes was 3 mm. The distance of the first row to the joint centre was 6 mm. A pin could be placed in one of the holes to serve as a spring attachment point (Figure 5). The forces acting on the distal phalanx, when a spring was applied, are shown in Figure 6. Spring manufacturers offer many different springs. Important spring parameters are: spring stiffness, rest length, maximum elongation, spring diameter and wire diameter. As the spring had to fit inside a finger, along the finger frame, the maximum spring diameter was set at 5 mm. Because a prosthetic hand has to function in a moist environment (e.g. ambient humidity or seepage from immersion of the hand) the springs had to be made of stainless spring steel. From the product range of standard helical springs of a large spring manufacturer (www.alcomex.nl) a total of 52 springs met both criteria.

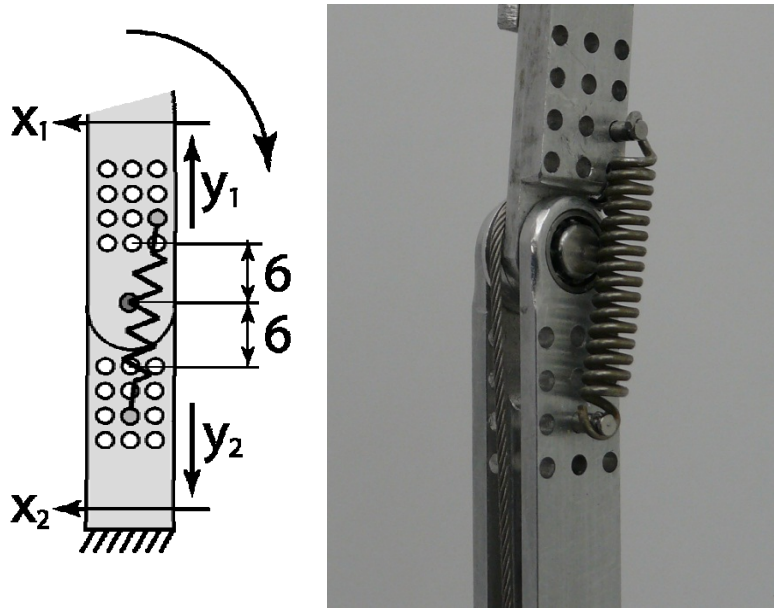


Figure 5 There were $3 \times 4 \times 3 \times 4 = 144$ different configurations to attach the spring to the mechanism. The distance between the centres of the joint was 3 mm. The curved arrow indicates the direction of the joint flexion. The figure shows configuration $x_1=1, y_1=2, x_2=2, y_2=3$, both schematically (left) and on the real mechanism (right).

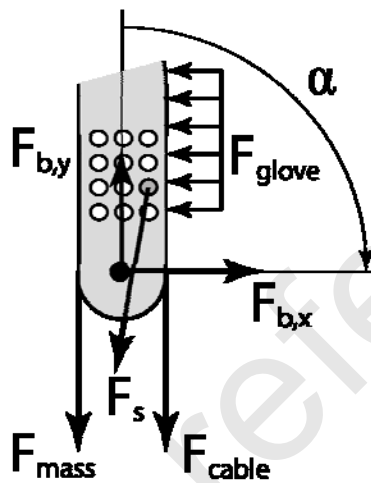


Figure 6 Forces acting on the distal phalanx, inducing torques around the joint axis. The forces of the cosmetic glove (F_{glove}) and the extension force of the counter mass (F_{mass}) induce a counter clockwise or positive torque. The cable force (F_{cable}) and the force of the compensation spring (F_s) induce a clockwise or negative torque. $F_{b,x}$ and $F_{b,y}$ represent the reaction forces in the joint, which do not contribute to the torque. The range of motion of the phalanx is indicated by arrow α .

Matlab model

A model was created in Matlab to select the optimal spring together with the optimal spring configuration. The parameters of the 52 selected springs were included in the model. The model calculated the force-displacement curve for every spring, in every configuration. The force-displacement curve of the compensation mechanism was added to the curve of the glove, to calculate the resultant curve (Figure 1). In the final step the algorithm selected the resultant curve

that had the smallest deviation from the horizontal axis. This is the combination of spring and attachment configuration that requires the lowest input torque.

Results

Figure 7 shows the measured joint torque as a function of the angle, for one cycle of 90° flexion and extension of both gloves. The torque increased almost linear with the joint angle. The area enclosed by the entire curve represents the amount of energy dissipated by the glove during one cycle. When the PVC glove was applied the finger required a torque range of 193 Nmm (from a minimum torque of -77 Nmm to a maximum torque of 116 Nmm). During one cycle 69 Nmm or mJ of energy was dissipated. The silicone glove required a torque range of 73 Nmm (from -33 Nmm to 40 Nmm). During one cycle 27 Nmm or mJ of energy was dissipated. Figure 7 shows the linear approximation of the joint stiffnesses of both gloves. The linear approximation of the joint torque and the joint angle θ (in degrees) could be described by $M_{pvc} = -72 + 2.07 \cdot \theta$ for the PVC glove and by $M_{silicone} = -29 + 0.73 \cdot \theta$ for the silicone glove.

To compensate the stiffness of the PVC glove, the MatLab model predicted the optimal result for spring TR480 (Alcomex.nl), in configuration $x_1=1, y_1=2, x_2=1, y_2=2$. In this configuration the system dissipated 37 Nmm or mJ of energy. For the silicone glove the optimal compensation was predicted for the TR390 spring, in configuration $x_1=1, y_1=1, x_2=1, y_2=4$. Figure 8 shows the predicted characteristic of the spring, together with the measured characteristic. In this configuration the system dissipated 21 Nmm or mJ of energy.

Figure 9 shows the resultant characteristics of the joint of both fingers, with the spring and the glove applied. The PVC glove in combination with the compensation mechanism, required a torque range of 81 Nmm (from a minimum torque of -36 Nmm to a maximum torque of 45 Nmm). This is 42 % of the required torque range of the uncompensated glove. During one cycle 67 Nmm or mJ of energy was dissipated. The silicone glove in combination with the compensation mechanism, required a torque range of 35 Nmm (from -10 Nmm to 25 Nmm), which is 48 % of the required torque range of the uncompensated glove. During one cycle 28 Nmm or mJ of energy was dissipated.

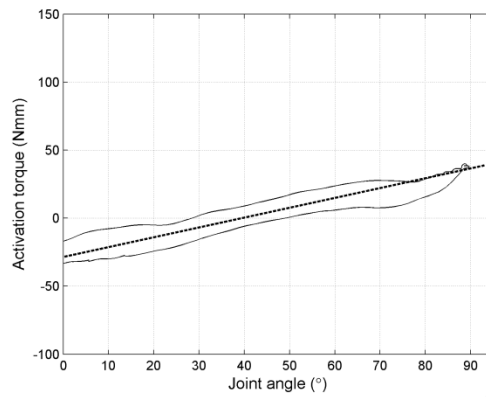
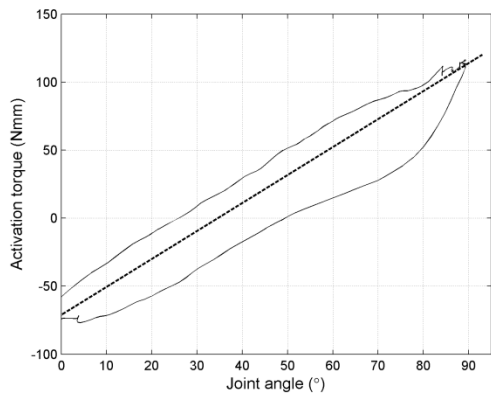


Figure 7 Measured joint stiffness (black line), and linear approached stiffness (dashed linear line), of the PVC glove (left) and the silicone glove (right). The diagram represents one cycle of 90° flexion and extension. The difference between the minimum and the maximum measured torque was 193 Nmm for the PVC glove and 73 Nmm for the silicone glove.

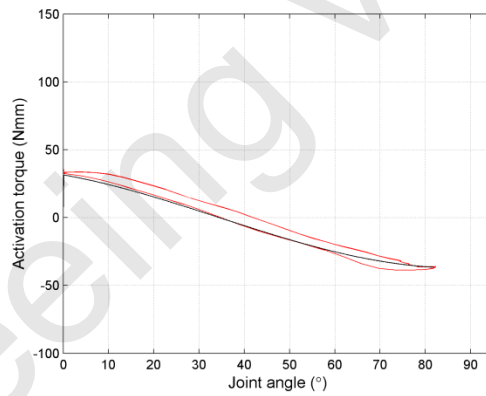
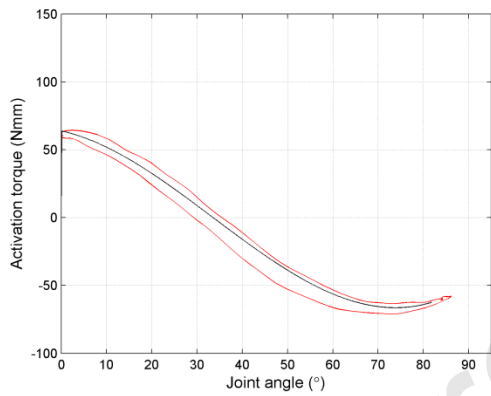


Figure 8 The predicted (black) and the measured (red) characteristic of the suggested spring, installed on the compensation mechanism in its optimal configuration. The TR 480 spring for compensation of the PVC glove (left). The TR 390 spring for compensation of the silicone glove (right). The diagram represents one cycle of 90° flexion and extension.

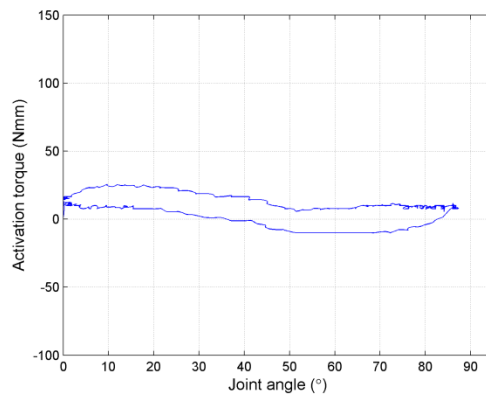
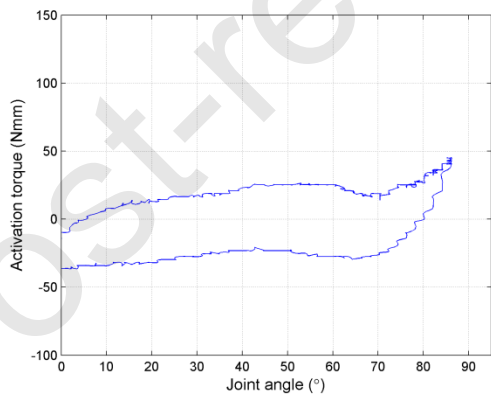


Figure 9 The resultant torque characteristic after the glove was placed over the finger. The difference between the minimum and the maximum measured torque was 81 Nmm for the PVC glove and 35 Nmm for the silicone glove. This is a reduction by 58 % and 52 % respectively, compared to the uncompensated glove.

Discussion

This study showed that it was possible to compensate the undesired joint stiffness caused by the cosmetic glove. The compensation mechanism reduced the required joint torque range of the PVC glove by 58 % and of the silicone glove by 52 %. It was however not possible to achieve a perfect compensation, as in Figure 1c. In the first place the glove stiffness was linearly approached. The real glove characteristic was however not entirely linear and had also a considerable amount of hysteresis (Figure 7). In the second place the real spring compensation characteristic might also have deviated a little from the measured characteristic (Figure 8, right), as the spring properties usually slightly differ from the properties specified by the manufacturer. Also the spring mechanism added a small amount of hysteresis. In the third place the optimal calculated resultant characteristic (Figure 9) was not exactly zero for every joint angle, due to the limited amount of springs and spring attachment locations. Despite these inaccuracies and hysteresis, the input torque was considerably reduced.

Implications for prosthetic hands

The mechanism can be applied to both body-powered and electric hands. In electric hands the compensation mechanism will help to reduce power consumption. Furthermore it might be possible to select other electric motors, which have a lower mass. Excessive prosthesis mass is currently one of the most important factors in prosthesis rejection.⁸ Finger movement requires a fast movement at a low torque, pinching requires a small movement at a high torque. Bi-phasic systems^{9,10} and systems with 'synergetic prehension'^{11,12} use this property to reduce the motor mass and required energy. When the torque is reduced by the glove compensation mechanism, these systems could be optimized to even further reduce energy consumption and to obtain a small reduction in motor mass. However the real benefit of the compensation mechanism will be for body-powered prostheses. As in these hands the user of the hand has to deliver the input energy himself. In many current hands this is a problem, as the forces the user has to deliver are too high.⁴ Applying the compensation mechanism to a prosthetic hand will help to reduce the force that the user has to deliver.

The study showed that the undesired stiffness of the cosmetic glove can be compensated by a relatively simple mechanism. All that is needed are a spring, the attachment points, and a small build-in space. The mechanism works for individual fingers, every single finger can be compensated. When applying the mechanism to a prosthetic hand, the biggest challenge will be the limited build-in space inside the finger. Other aspects, e.g. costs and mass will be of minor influence. Because of the small number of extra required parts and the low mass of the parts (less than 1 gram per joint), the glove compensation will only add little extra mass, relative to the mass of a standard prosthetic hand (~500 gram).

Inner glove compensation?

Beside a cosmetic glove, many prosthetic hands also have an inner glove. The inner glove gives the hand its shape and it provides an extra protection of the mechanism against the environment. From a mechanical point of view the inner glove has the same undesired properties as the cosmetic glove. The inner glove is even thicker and stiffer than the cosmetic glove and therefore it dissipates more energy than the cosmetic glove and it requires a higher input force.⁴ Although it might also be possible to compensate the stiffness of the inner glove, this will be harder to achieve due to its higher stiffness. However, the use of an inner glove is not a necessity. Hands like the Becker Imperial hand or the Hosmer APRL hand do not use an inner glove. Also new hands like the i-limb and the bebionic do not use inner gloves. Because of its negative mechanical properties the use of an inner glove should be avoided in future designs.⁴ Omission of the inner glove will also leave more build-in space for the compensation mechanism.

Other applications

This study was performed to solve the problem of the undesired stiffness of finger joints of prosthetic hands, caused by the cosmetic glove. The presented solution can however be used for every joint which has an undesired joint stiffness, e.g. a bundle of cables or a hydraulic hose attached to a joint of a robot arm.

Strengths and limitations

Although the glove compensation principle was already described in earlier studies,^{2,6,7} it was still unknown whether it would be feasible to design a mechanism that would fit inside a prosthetic hand. This study showed that it was even possible to fit such a mechanism inside a finger. The mechanism used standard springs and was adjustable to different gloves, even when the gloves were made of different materials and had different stiffness characteristics. This enabled the use of different gloves, which is important as there are various different glove manufacturers who produce a broad range of PVC and silicone cosmetic gloves of different sizes and thicknesses.

The most important limitation of the compensation mechanism was the hysteresis band, which was largely caused by the hysteresis in the glove. The compensation mechanism added a small amount of extra friction. As a result of the hysteresis band, the system always needed an input torque and always dissipated energy during motion. A strength of the presented compensation mechanism is that it only required two extra joints (the attachment points of the spring), so the added amount of joint friction was small.

Conclusions

This study showed that the undesired positive stiffness in the joint of the cosmetic glove, can be compensated with a relatively simple negative stiffness mechanism, by using a standard helical tension spring. The mechanism was designed, built and tested. The entire mechanism fit inside a finger of a standard cosmetic glove. The mechanism could compensate the positive stiffness of a silicone cosmetic glove, as well as of a much stiffer PVC glove. The compensation mechanism reduced the required input torque range by 58 % for the PVC glove and by 52 % for the silicone glove. The addition of the compensation mechanism did not significantly change the total energy dissipation of the finger joint.

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