

Evaluation of the Flexibility of Protective Gloves

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Two mechanical methods have been developed for the characterization of the flexibility of protective gloves, a key factor affecting their degree of usefulness for workers. The principle of the first method is similar to the ASTM D 4032 standard relative to fabric stiffness and simulates the deformations encountered by gloves that are not tight fitted to the hand. The second method characterizes the flexibility of gloves that are worn tight fitted. Its validity was theoretically verified for elastomer materials. Both methods should prove themselves as valuable tools for protective glove manufacturers, allowing their existing products to be characterized in terms of flexibility and the development of new ones better fitting workers' needs.

flexibility stiffness protective glove

1. INTRODUCTION

Hand injuries represent a major source of accidents, in particular at the workplace. In Québec, Canada, they accounted for 17% of all occupational lesions compensated for by the Québec Occupational Health and Safety Commission¹ between 2001 and 2004 [1]. Protective gloves can reduce the occurrence of such injuries, but with a price in terms of loss of dexterity and sensitivity, and additional muscular constraints, among others [2]. This can lead to either workers not being able to perform adequately their tasks, or deciding not to wear protective gloves. In both cases, the risk of injury is increased.

Flexibility, which contributes to dexterity and sensitivity, is one of the major properties that

define how a glove interferes with workers' ability to perform their tasks. Some studies have considered the biomechanical aspects of protective glove use on the deployment of the maximum grip force. It was shown, e.g., that wearing protective gloves reduces the maximum gripping force by 7–30% [3]. Other authors have developed a method based on surface electromyography to assess the effect of glove wearing on the activation and fatigue of several forearm muscles [4]. However, procedures involving human subjects are prone to high levels of interindividual variability. On the other side, purely mechanical methods have been developed for characterizing film and fabric stiffness or flexibility (its inverse) [5, 6, 7]. Most of them are based on uniaxial bending, which may not be representative of the type of deformations

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sustained by gloves in usage. On the other side, the ASTM D 4032 standard [7], which provides a method for measuring the stiffness of fabrics, makes use of a circular bend procedure, thus creating multidirectional deformations. According to the ASTM D 4032 method, a flat-headed cylindrical probe forces a folded piece of fabric through a circular orifice in a platform. The maximum force required to push the fabric through the orifice is measured and used as an indication of the fabric stiffness.

In order to characterize the flexibility of protective gloves without human subjects, the free-deforming method has been developed based on the same principle as the ASTM D 4032 standard [7], but with a larger gap between the probe head and the orifice edge, and a more relevant shape for the probe. This method measures mostly out-of-plane material deformations and can be seen as describing the behavior of gloves that are not tight fitted to the hand.

For simulating the behavior of gloves that are worn tightly fitted, a fixed technique is also proposed; it uses the same type of probe geometry as the free-deforming method, but with securing the glove material along the circumference of the orifice. In that case, deformations are mostly in the plane of the tested material. The measurements performed on elastomer gloves were compared to a theoretical description based

on the Mooney formalism [8] using uniaxial tensile tests.

2. EXPERIMENTAL

2.1. The Free-Deforming Technique

As for the ASTM D 4032 standard [7], this technique is based on the use of a probe to push a sample through an orifice drilled in a platform. However, some distinctive features of the free-deforming technique are dictated by the requirements related to the measurement of protective gloves. First, to account for the fact that gloves are thicker than fabrics, the value of the gap between the probe head and the orifice edge is almost doubled. Second, in order to limit the stress concentration at the probe head and to better simulate the type of deformations applied to gloves while they are in use, a cylindrical probe with a spherical-conical shaped head is used, producing double curvature deformations [9]. Third, to account for the influence of glove fingers, the diameter of the probe is maintained at a constant value up to the top, as illustrated in Figure 1, which displays the experimental set-up inserted into a 1137 Instron, USA, tensile testing frame with a glove positioned palm up above the orifice.

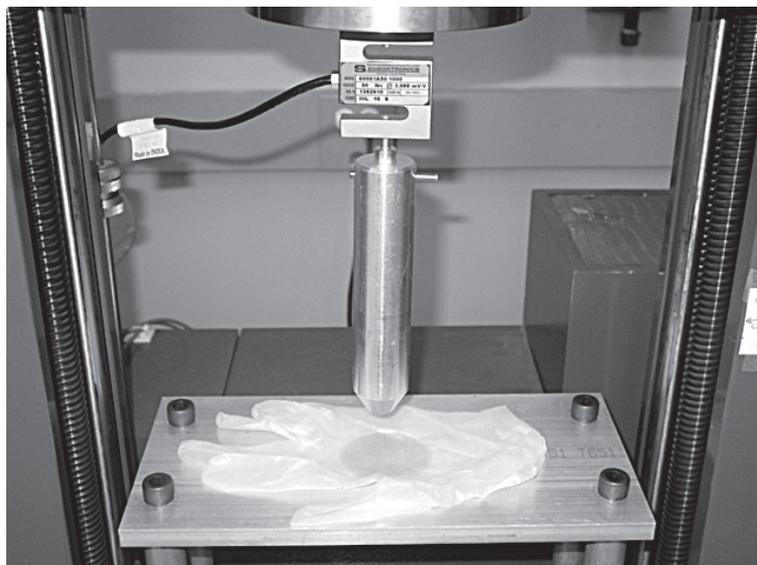


Figure 1. Experimental set-up of the free-deforming technique.

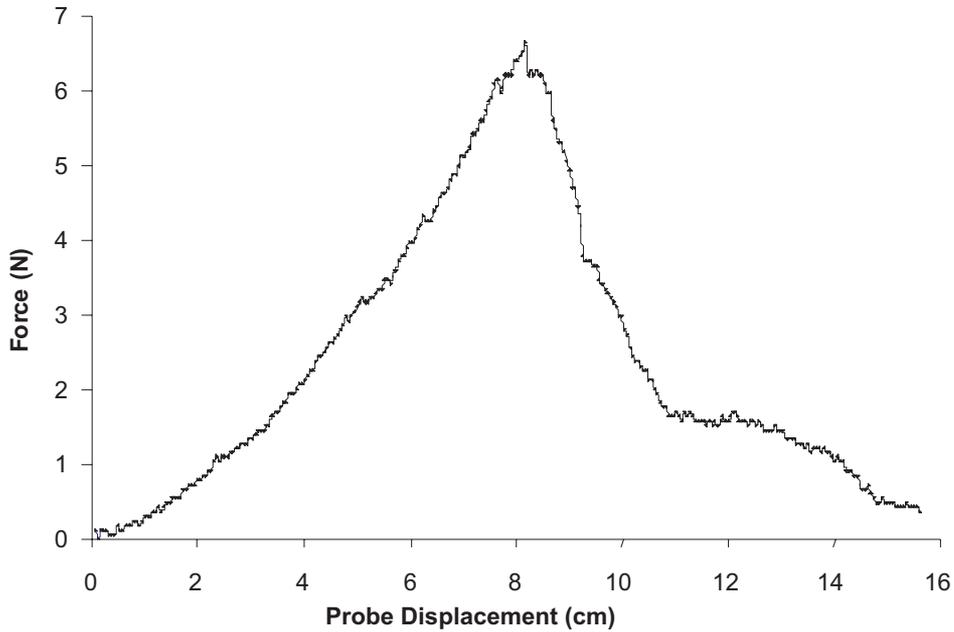


Figure 2. Example of the force displacement curve measured as a glove is pushed through the orifice.

Force-displacement data are recorded by the testing frame as the glove is pushed by the probe through the orifice, an example of the corresponding curve being shown in Figure 2. Principal and secondary maxima correspond to the passage of glove fingers through the orifice. In terms of data analysis, the value of the maximum force was extracted from the force-displacement data, in accordance with the ASTM D 4032 standard [7] where it is used as

a characterization of fabric stiffness. In addition, following some authors studying fabric comfort [10], the total work necessary to push the entire glove through the orifice was also calculated, this work being proportional to the deformation energy, itself inversely proportional to flexibility.

2.2. The Fixed Technique

In order to obtain a realistic determination of the flexibility of tight fitting gloves, the set-up

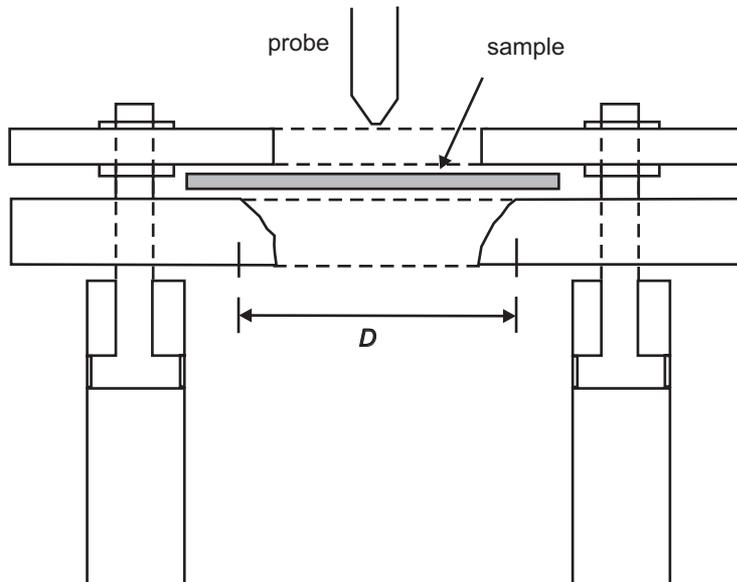


Figure 3. Set-up of the fixed technique. Notes. *D*—orifice diameter.

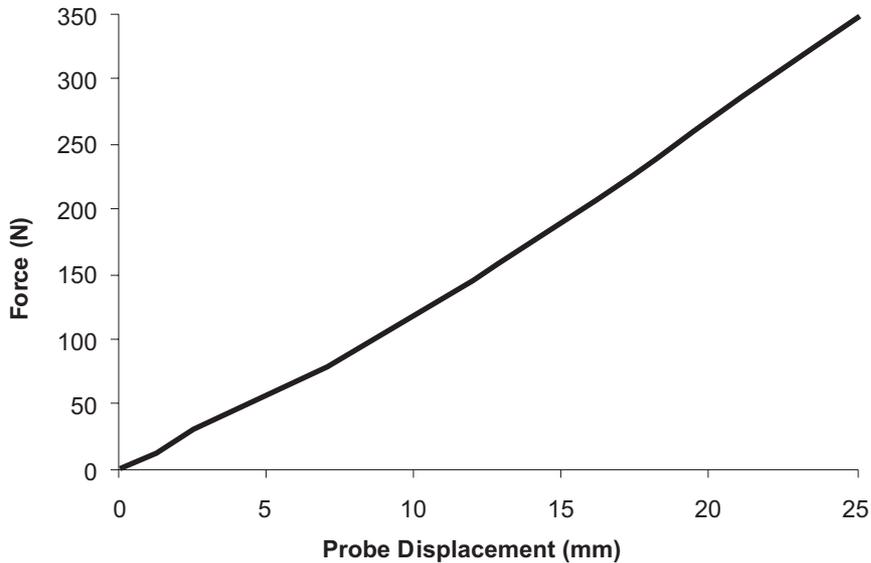


Figure 4. Example of a force deformation curve measured with the fixed technique.

described in section 2.1. was modified so that a layer of the glove material taken in the palm area was secured along the circumference of the orifice (Figure 3). The same geometry of the probe was used and the deformation of the membrane was recorded as a function of the force applied by the probe.

Figure 4 displays an example of a force displacement curve measured for a natural rubber glove. In the configuration corresponding to the fixed technique, the stiffness of the material is characterized as the slope of the force displacement curve, flexibility being its inverse.

2.3. Materials and Methodology

Ten models of protective gloves from two manufacturers (Best Glove Manufacturing, Canada, and Ansell Occupational Healthcare, USA) were measured using the free-deforming technique. Some were made of pure elastomer, one of a knit fabric, and some featured a knit liner dipped in a polymer. The description of the composition of each glove is provided in Table 1 along with its thickness measured in the middle of the palm section. For each model, five measurements were performed on different gloves to ensure that the measurement uncertainty

included property variability between gloves of the same model.

Five models of gloves were also characterized with the fixed technique, three of them elastomers, along with two thicknesses of a neoprene membrane. Table 3 includes information about glove and membrane materials. As for the free-deforming test, each result is the average of five measurements.

3. THEORETICAL DESCRIPTION OF THE FIXED TECHNIQUE

In order to validate the developed fixed technique, a theoretical description of the deformation of elastomer materials is presented in this section.

As shown in Figure 5, the surface of the deformed membrane can be divided into three zones: a lower one (zone A) in contact with the spherical part of the probe head, a middle one (zone B) in contact with the conical part of the probe head, and a top one (zone C) not in contact with the probe. The force applied by the probe is the sum of two contributions [11]: F_A relative to zone A and F_B relative to zone B.

For the description of the elastomer mechanical properties, the Mooney formalism, valid for elastic, isotropic and incompressible materials,

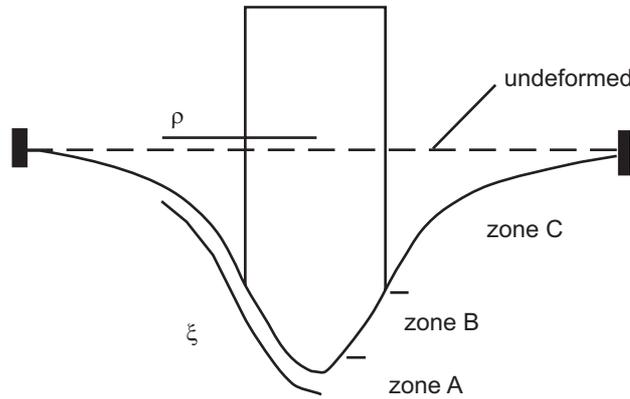


Figure 5. Schematic representation of the deformed membrane in the fixed technique.

has been used in its two-constant version by the way of the Mooney strain energy function W [8]:

$$W(\lambda_1, \lambda_2) = C_1(\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2}\lambda_2^{-2} - 3) + C_2(\lambda_1^{-2} + \lambda_2^{-2} + \lambda_1^2\lambda_2^2 - 3), \quad (1)$$

where λ_1, λ_2 —radial and circumferential extension ratios in the (ρ, ξ) cylindrical coordinate system respectively (Figure 5).

The Mooney-Rivlin constants, C_1 and C_2 , can be obtained by uniaxial tensile tests performed according to the ASTM D 412 standard [12]. The resulting stresses T_1 and T_2 per unit edge length respectively along the radial and the circumferential directions become

$$T_1 = 2h \left(\frac{\lambda_1}{\lambda_2} - \lambda_1^{-3}\lambda_2^{-3} \right) (C_1 + \lambda_2^2 C_2),$$

$$T_2 = 2h \left(\frac{\lambda_2}{\lambda_1} - \lambda_1^{-3}\lambda_2^{-3} \right) (C_1 + \lambda_1^2 C_2), \quad (2)$$

with h —thickness of the membrane.

In zone A, at the tip of the probe, the membrane is in an equibiaxial stress state, leading to $\lambda_1 = \lambda_2 = \lambda_0$. The force applied by the probe on the membrane inside zone A can be expressed as

$$F_A = 12RC_1 h (1 - \lambda_0^{-6}) (1 + \alpha \lambda_0^2), \quad (3)$$

with R —radius of curvature of the spherical part of the probe head and $\alpha = C_2/C_1$.

In zone B corresponding to the conical part of the probe head, the force can be expressed as

$$F_B = 4\pi(R_2 - R_1) \cos \theta C_1 h \left(\frac{\bar{\lambda}_1}{\bar{\lambda}_2} + \frac{\bar{\lambda}_2}{\bar{\lambda}_1} - \frac{2}{\bar{\lambda}_1^3 \bar{\lambda}_2^3} + \alpha \left(2\bar{\lambda}_1 \bar{\lambda}_2 - \frac{1}{\bar{\lambda}_1^3 \bar{\lambda}_2} - \frac{1}{\bar{\lambda}_2^3 \bar{\lambda}_1} \right) \right), \quad (4)$$

where θ, R_1, R_2 —angle and two radii of the conical part of the probe head respectively; $\bar{\lambda}_1, \bar{\lambda}_2$ —average values of λ_1 and λ_2 over the zone B section of the membrane.

4. RESULTS AND DISCUSSION

Table 1 displays the results in terms of maximum force and total work values measured with the free-deforming method for 10 models of protective gloves. Both parameters lead to the same ranking of the gloves on a decreasing flexibility scale (rank 1 corresponds to the most flexible glove). Also provided in Table 1 is each glove composition and its total thickness (front and back layers together) measured in the middle of the palm.

The low variability of the results as well as the fact that both the maximum force and the total work lead to the same ranking of glove flexibility show this free-deforming technique as a valuable tool for the determination of the flexibility of loosely fitting protective gloves by mechanical means. However, these flexibility measurements may include a slight parasitic contribution of

TABLE 1. Results of the Free-Deforming Technique Measurement for 10 Models of Protective Gloves (SD)

| Model | Material | Thickness (mm) | Maximum Force (N) | Total Work (N·cm) | Ranking |
|--|-------------------------------|----------------|-------------------|-------------------|---------|
| Ansell ¹ Cannery & Handlers 392 | NR | 1.12 (0.05) | 3.8 (0.3) | 0.51 (0.04) | 1 |
| Ansell Goldknit Kevlar® 70-225 | Kevlar® knit | 4.50 (0.10) | 22.5 (2.6) | 7.20 (0.70) | 2 |
| Ansell Hyflex 11-900 | nitrile rubber on cotton knit | 2.03 (0.08) | 22.6 (0.9) | 7.70 (1.00) | 3 |
| Best ² Nitri-Solve® 747 | nitrile rubber | 1.17 (0.04) | 51.6 (2.0) | 22.00 (1.80) | 4 |
| Best Latex HD® 55 | NR | 2.11 (0.08) | 130 (17) | 51 (11) | 5 |
| Best KPG® 960 | PVC on cotton knit | 3.71 (0.03) | 222 (18) | 93 (3) | 6 |
| Best Skinny Dip Aramid® 4811 | NR on Kevlar® aramid knit | 4.30 (0.30) | 235 (32) | 98 (19) | 7 |
| Best The Original Nitri-Flex® 4000P | nitrile rubber on cotton knit | 1.65 (0.06) | 250 (22) | 99 (12) | 8 |
| Ansell PowerFlex 80-100 | NR on poly/cotton knit | 3.60 (0.30) | 267 (21) | 110 (7) | 9 |
| Best Nitri-Pro® 7000P | nitrile rubber on cotton knit | 1.70 (0.40) | 433 (65) | 138 (52) | 10 |

Notes. 1—Ansell Occupational Healthcare, USA; 2—Best Glove Manufacturing, Canada; NR—natural rubber; PVC—polyvinyl chloride.

the properties of the surface of the glove due to friction developing between the glove and the surface of the orifice edge.

The theoretical validation of the fixed technique for the determination of tight fitting glove flexibility was performed by comparing the measured and calculated values of the force corresponding to the position where the contact zone between the membrane and the probe head reaches the top of the conical part of the probe head (corresponding to the schematic in Figure 5). Table 2 provides the results for a nitrile rubber and two natural rubber gloves as well as for a neoprene membrane, the thickness value corresponding to the measured layer of material.

The force values correspond within the error bars. Indeed, for elastomers, and by extension, isotropic materials, material flexibility is independent of the type of deformation. For such

materials, flexibility can be characterized by a simple uniaxial tensile test. However, for gloves made of anisotropic materials, a multidirectional deformation measurement such as the fixed technique is required.

The results in terms of the calculated flexibility coefficient (the inverse of the slope of the force displacement curve) are displayed in Table 3 for five models of gloves as well as for two thicknesses of a neoprene membrane. Due to limitations in the load cell capacity of the testing frame used for these measurements, the total extent of the linear part of the force displacement curve was not obtained for the composite gloves, leading to a slightly higher measurement uncertainty.

For natural rubber gloves and neoprene membranes, for which two thicknesses are available, the flexibility coefficient is inversely

TABLE 2. Comparison of the Measured and Calculated Force for the Validation of the Fixed Technique (SD)

| Material/Model | Thickness (mm) | Measured Force (N) | Calculated Force (N) |
|---|----------------|--------------------|----------------------|
| Natural rubber (Ansell ¹ Cannery & Handlers 392) | 0.58 (0.03) | 162 (19) | 153 |
| Neoprene membrane | 0.40 (0.01) | 239 (33) | 218 |
| Natural rubber (Best ² Latex HD® 55) | 1.09 (0.04) | 324 (49) | 299 |
| Nitrile rubber (Best Nitri-Solve® 747) | 0.69 (0.03) | 495 (60) | 449 |

Notes. 1—Ansell Occupational Healthcare, USA; 2—Best Glove Manufacturing, Canada.

TABLE 3. Values of the Flexibility Coefficient Measured With the Fixed Technique (SD)

| Model | Material | Thickness (mm) | Flexibility Coefficient (mm/N) |
|--|-------------------------------|----------------|--------------------------------|
| Ansell ¹ Cannery & Handlers 392 | natural rubber | 0.58 (0.03) | 0.118 (0.010) |
| Membrane | neoprene | 0.40 (0.01) | 0.080 (0.009) |
| Best ² Latex HD® 55 | natural rubber | 1.09 (0.04) | 0.062 (0.007) |
| Best Nitri-Solve® 747 | nitrile rubber | 0.69 (0.03) | 0.036 (0.003) |
| Membrane | neoprene | 1.57 (0.07) | 0.023 (0.002) |
| Ansell Goldknit Kevlar® 70-225 | Kevlar® knit | 2.13 (0.04) | 0.014 (0.002) |
| Ansell Hyflex 11-900 | nitrile rubber on cotton knit | 1.07 (0.04) | 0.0043 (0.0006) |

Notes. 1—Ansell Occupational Healthcare, USA; 2—Best Glove Manufacturing, Canada.

proportional to the thickness of the material, which is consistent with Equations 3 and 4. With this fixed method, non-elastomer-based gloves show a much smaller flexibility compared to elastomer ones, producing a different glove ranking than that obtained with the free-deforming technique. To circumvent this reduced in-plane flexibility of composite materials while taking advantage of their increased protective properties, composite gloves often include uncoated or more flexible material on the back side of the glove and on knuckles to allow more movement freedom for the user.

5. CONCLUSIONS

Two methods have been developed for the mechanical characterization of the flexibility of protective gloves. The free-deforming technique simulates the behavior of gloves that are worn loosely fitted and undergo mostly out-of-plane deformations, while the fixed technique characterizes the flexibility of tight fitting gloves. The validity of the fixed method was theoretically validated for elastomer materials. Both techniques produced different rankings for the tested gloves in terms of their flexibility, illustrating the importance of a careful selection of materials during glove design and the advantage of multipart configurations with properties of each glove section being tailored to the type and amplitude of deformations undergone at that location.

In order to verify the validity of the glove flexibility rankings provided by these two methods, the same gloves will be tested by human subjects, using both a biomechanical

technique based on surface electromyography and a psychophysical evaluation test. The ultimate goal is to obtain a mechanical test method, i.e., not involving human subjects, able to characterize glove flexibility as users perceive it. Much simpler to implement, such mechanical method could be easily used by protective glove manufacturers to provide quantitative information about their product's flexibility, thus allowing for an easier process of glove selection by users. In addition, the availability of such a characterization tool could provide manufacturers with the incentive as well as the capability for improving the flexibility of their products while maintaining the same level of protection, such increased flexibility translating into improved dexterity and sensitivity for users.

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