COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Impact of material characteristics of cloth on the gripping force and performance of finger grippers*

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INFO

CDATP, ISSN 2701-939X
Peer reviewed article
2024, Vol. 5, No. 2, pp. 222-233
DOI 10.25367/cdatp.2024.5.p222-233
Received: 27 Juni 2023
Accepted: 05 August 2024
Available online: 29 December 2024

ABSTRACT

With the rising demand for automation and robotization in the textile industry, a variety of gripping solutions for textile materials has been developed in recent years. The increase in finger grippers is noticeable, however, a difference in the applicability and the holding force of finger grippers can be observed. Understanding the correlation between characteristics of the picked up textile materials, the style, coating and material of the gripper and the repeatability of the pick-up process and the gripping force is crucial for their successful industrial integration. In this paper, the correlations between the properties of the different textiles and the gripping performance of a finger gripper are investigated. Bending stiffness, lateral compressibility, friction parameters and other textile characteristics are compared to the gripping force of the gripper with the selected textiles. The most important parameters are selected by principal component analysis and investigated for correlation.

Keywords
automation,
gripping solutions,
gripping force,
principal component analysis

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1 Introduction

As the interest in process automation increases in the textile industry, for sustainability, political and labor market reasons [1], so does the interest in and need for gripping solutions developed for textile applications. Textile products have large deviations of their properties like air permeability and bending rigidity. Finding suitable grippers for each product is a challenging task. In order to satisfy the need for automation the number of gripping solutions developed for textile applications increases as well [1-15].

Numerous studies have been conducted on the efficiency and requirements for handling textile materials. Already in 1991, Schulz et al. worked on and reviewed the suitability of different gripper types for textile materials [16]. Dragusan et al., in an effort to develop a dress gripper, also studied the force necessary to break the grip of a gripper [12]. Lien et al. investigated the Coanda effect with different textile materials [17]. Drigalski et al. developed a method with which textile materials could be separated and classified by the response of a rubbing motion of the fingers on the material [18,19].

In current and past research, specific interest has been shown on gripper sensor and feedback systems [1,12,15,18,20]. However, to the authors knowledge, little and only partial research has been conducted on the influence of specific textile characteristics on the performance of grippers. E.g., Ebraheem et al. conducted a study on the correlation of air permeability of fabrics and gripper performance [20]. In this paper, the impact of different textile characteristics on the performance of a finger gripper, namely pick up ability, holding force and the ply separation ability of the gripper are studied. The results can be used to predict the performance of said gripper on a variety of materials without independent gripper testing.

2 Material characterization

In the current study, textile materials with different masses per unit area, different fabric types (woven and knitted) and different fields of applications were gathered. Materials used in common production of daily clothing and workwear, as well as some technical textiles are included (Table 1).

Of each material, two sets of specimens were prepared: a set of round specimens with a diameter of 100 mm and a set of tensile test specimen. The tensile test specimen from woven fabrics have dimensions of 300 mm x 50 mm and from knitted fabric 200 mm x 100 mm [21]. All materials were then characterized by the material tests as follows.

Table 1. List of materials.

Material name	Fabric type	Fiber material (%)	Mass per unit area (g/m^2)
PO1	Woven, laminated with foam	Polyester	358.8
PG1	Weft knitted	Nylon/Lycra 75/25	345.6
PG2	Weft knitted	Nylon/Lycra 73/27	339.6
BU1	Woven – plain	Polyester	148.0
R1	Woven – plain	Nylon with polyurethane finish	265.0
KG1	Woven – plain	Polyester/Cotton 65/35	108.1
KG2	Weft Knitted	Viscose/Elastane 94/6	200.0
KG3	Woven – plain	Cotton	145.2
KG4	Woven – Jacquard	Polyester/Viscose 80/20	103.4
KG5	Woven – plain	Polyester	79.3
KG6	Woven – twill (denim)	Cotton/Elastane 98/2	228.6
KG7	Woven – plain	Linen	228.6
KG8	Woven – plain	Cotton	137.9
KG9	Woven – corduroy	Cotton	150.0
KG10	Woven – twill (denim)	Polyester	100.0
KG11	Woven – plain weave	Cotton	200.0

2.1 Mass per unit area

The first test executed was the measurement of width, length and weight of the prepared tensile test specimens. The nominal mass per unit area, as provided by the producer, was compared to the measured values.

2.2 Bending stiffness

The tested mass per unit area is required for the evaluation of the bending stiffness of the material according to the cantilever principle. This was performed using a Cetex Cantilever ACTM 200 [22] with a slider width of 50 mm and a testing speed of 120 mm/min. The tensile test specimens were used for this test.

2.3 Air permeability

The air permeability was measured using a Textest FX3300 device following DIN EN ISO 9237 with three samples per material. During measuring the air permeability, attention must be paid to possible air losses due to air flow along the fibers through the specimen holder. To avoid measurement errors due to air flow along the fibers, the air flow was first measured with only the specimen, and then with an airtight medium on top of the specimen. Using the airtight medium, exclusively the air flow along the length of the fibers was measured, which could then be subtracted from the measurement without the airtight medium, resulting in a realistic value for air permeability with minimal error. E.g., the air permeability for material PO1 was measured as 98.17 $l/m^2/s$. The air permeability of PO1 with an airtight medium positioned above the material was 4.89 $l/m^2/s$. Accordingly, the air permeability of PO1 is 93.3 $l/m^2/s$.

2.4 Friction test

The static and sliding friction coefficients of the textile specimen and the silicone fingers of the investigated gripper were determined by fixing a cut-out of the silicone finger on a sled attached to a tensile testing machine (Fig. 1) **Fehler! Verweisquelle konnte nicht gefunden werden.**. The sled was positioned on the specimen and pulled along the length of the specimen for 100 mm with 100 mm/min speed on a modified tensile testing machine.

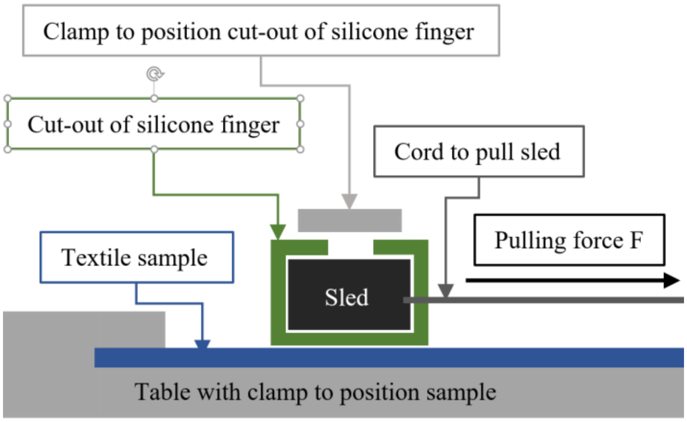


Fig. 1 Schematic of friction test setup.

The friction coefficients were calculated using (1), with μ_D and μ_S being the static and dynamic friction coefficients, and F_D and F_S being the dynamic and static frictional force.

$$\mu_{D,S} = \frac{F_{D,S}}{F_N} \qquad (1)$$

2.5 Compressibility

The compressibility Z of the textile materials, in this paper, is defined as the relative difference of the DIN 53885, see (2), the pressure in this test was varied from 0.2 kPa and 2 kPa to 2 kPa and 20 kPa, as a finger gripper was expected to apply significantly more pressure than 2 kPa. This presents a simple method of evaluation of the lateral elasticity of the fabrics, which is important when the fabrics get touched and pressed by grippers.

$$Z = \frac{d_{2kPa} - d_{20kPa}}{d_{2kPa}} \qquad (2)$$

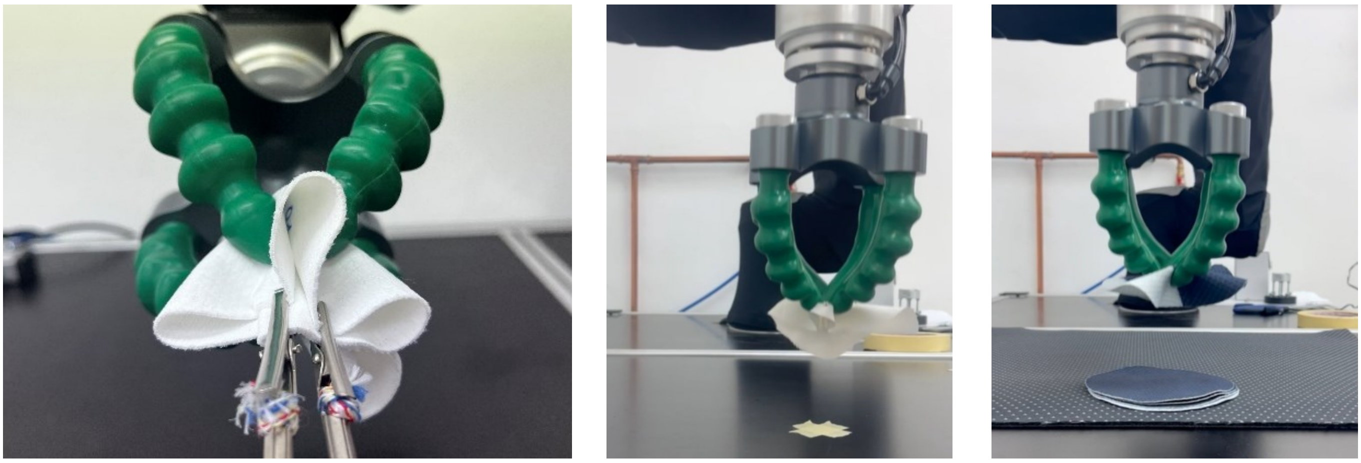
3 Investigation

For the investigation of the interaction of textile materials and gripper, the OFG finger gripper [23], produced by Schmalz GmbH, was used. A silicone gripper was selected, as the silicone fingers were expected to show higher holding forces with textile materials than comparable metal finger grippers. A number of finger grippers with active joints and sensors are available, and, with fitting parameters, are expected to perform better with textile materials than the pneumatic gripper. However, this study was aimed to benchmark the general performance of a finger gripper movement pattern with textile materials. The simpler, pneumatic finger gripper chosen meets this requirement.

The gripper performance was measured in five tests:

- Picking up a single textile round sample from a smooth wood surface,
- picking up a single textile round sample from a textile car seat cover surface,
- gripping force test,
- separating single textile samples from a stack of samples located on a smooth wooden surface,
- separating single textile samples from a stack of samples located on a car seat cover surface.

Five round samples of each material with a diameter of 100 mm were tested in each test. The results of the pick-up tests and separation tests, further referred to as ply separation, were recorded as binary values of zeros and ones for “not successful” and “successful”. “Successful” was awarded when a sample could be picked up and transported for more than 500 mm without being dropped or separated from the stack and transported respectively (Fig. 2b and 2c). In the gripping force tests, the textile round samples were positioned in the finger gripper and firmly gripped (Fig. 2a). After a firm grip was established, the edges of the sample were clamped and the clamps attached to a Sauter FH 100 force gauge with a capacity of 100 N. While positioning the fabric, the folds, which are formed in the grip, must be placed realistically and with repeat accuracy (Fig. 2). The maximal gripping force, corresponding to the static friction, was measured before the first slip occurred, and that value was recorded.



a) b) c)

Fig. 2 Images of the experimental setup with a) the textile sample placed in gripper with fold pattern and clamp position for gripping force measurement, b) pick-up test off of a smooth surface and c) ply separation test on a car seat cover.

4 Method of data revision and analysis

The data series was analyzed using Principal Component Analysis (PCA) and the Python library “statsmodels” [24]. The PCA is a method to analyze data sets, where different variables might be correlating. K-dimensional data is reduced to n-dimensional plots by determining the eigenvectors of the covariance matrix, which are the principal components. The first and second principal components, or the axes of the PCA plot, are the eigenvectors with the largest and second largest eigenvalues.

The textile characterization data was first collected in a data frame containing the mean values of the test data for each test and material. The data frame thus contains a matrix with 16 rows, one row per material, and 6 columns: bending stiffness, mass per unit area, compressibility, air permeability and the static and dynamic friction coefficients.

The gripper performance matrix contains 16 rows and five columns: the mean values of the pick-up tests off two surfaces, the gripping force test, and ply separation test off two surfaces. For the repeatability tests (pick up and ply separation), binary results were obtained. An average of the five results is the mathematical probability of a successful event.

The results of a PCA of the textile characterization, without gripper performance data included, are depicted in Fig. 3. The blue marks represent the sixteen assessed textile materials. Their positions in the matrix are a result of the eigenvector analysis of the PCA. The dominant textile characteristics in each section of the plot were marked using arrows. The further a data point is located from the origin, the more dominant the characteristic in that area is for the model.

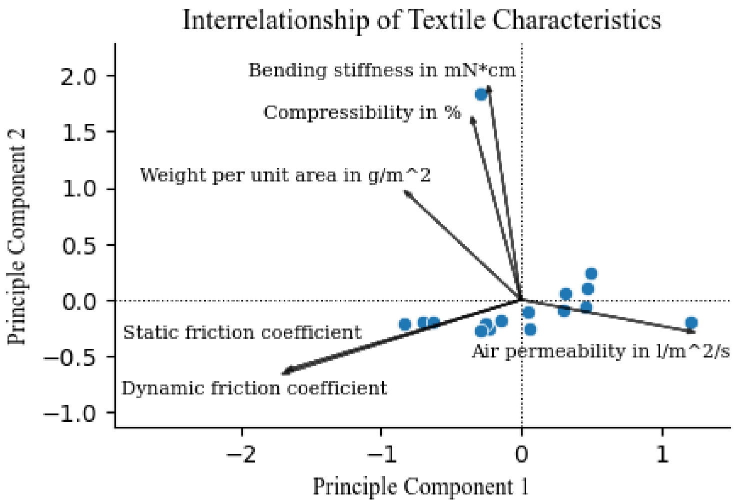


Fig. 3 PCA plot to show interrelationship of textile characteristics.

To analyze the impact and influence of textile characteristics on the handling of textile materials, a targeted PCA analysis was conducted. In this, the PCA plot was expanded by labeling the data points representing textile materials according to the test results of the gripper tests.

While the targeted PCA analysis allows for qualitative assessment of connections and correlations, the PCA plots show no quantitative measure for correlation. Thus, the correlation coefficient r is used, to show linear relationships between the characteristic and performance metrics. The correlation coefficient has a range of $-1 \leq r \leq 1$, with $r = -1$ indicating a full negative correlation and $r = 1$ indicating a full positive correlation. As the sample size in this investigation is relatively small with $n = 23$, the correlation coefficient indicating significance is selected to be $r_{sig} = \pm 0.7$ [25].

5 Results

First, the holding force was evaluated, as this was deemed the least challenging test for the gripper. The result plot of this analysis is shown in Fig. 4.

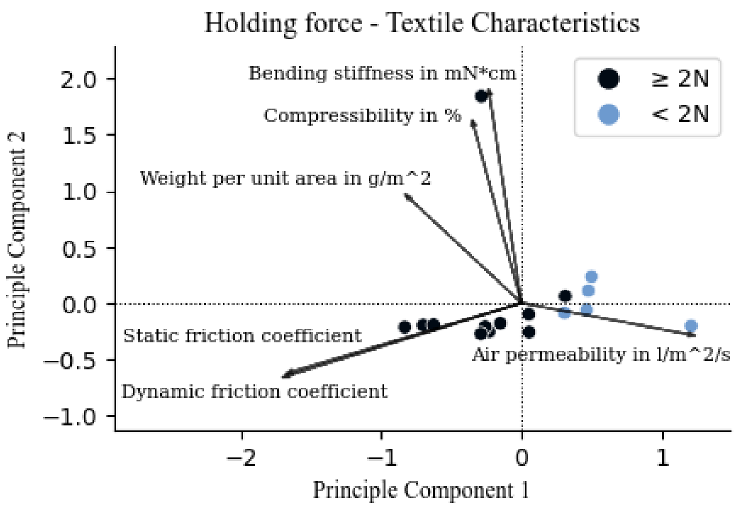


Fig. 4 PCA plot to show interrelationship of textile characteristics with the holding force.

While friction coefficients and bending stiffness do not appear to have an adverse effect on the holding force, at first sight, air permeability appears to have an impact. Both irregularly high and low air permeability values appear to correlate with a reduction of the holding force, see materials BU1, KG1, KG5, KG7 and KG8 in Table 2.The static friction coefficients of the five materials with a holding force < 2 N are < 1 (Table 2).

Table 2. Holding force, air permeability and static frictions coefficients of the 16 materials.

Material name	**Holding force (N)**	**Air permeability ($l/m^2/s$)**	**Static friction coefficient**
PO1	2.73	93.27	1.02
PG1	2.30	110.45	1.25
PG2	2.87	125.60	1.28
R1	2.17	551.71	1.12
BU1	1.75	0	0.86
KG1	1.75	331.10	1.00
KG2	2.06	376.02	1.16
KG3	2.40	65.44	1.19
KG4	2.02	154.88	1.08
KG5	1.71	3779.5	0.92
KG6	2.48	60.28	0.95
KG7	1.98	545.50	0.91
KG8	1.97	591.38	0.95
KG9	2.40	122.93	1.28
KG10	2.23	103.07	1.14
KG11	2.30	276.28	1.18

Applying the method of targeted PCA to the pick-up test from a smooth surface, the plot as depicted in Fig. 5 is the result. To aid simple evaluation, the probability values of a successful pickup were further reduced to greater or equal and smaller than a probability of 0.8. Only two materials have a probability of less than 0.8 for a successful pick up, materials P01 and R1. During measuring the bending stiffness, those two materials were the only to record a bending stiffness greater than 4 mN·cm (Table 3).

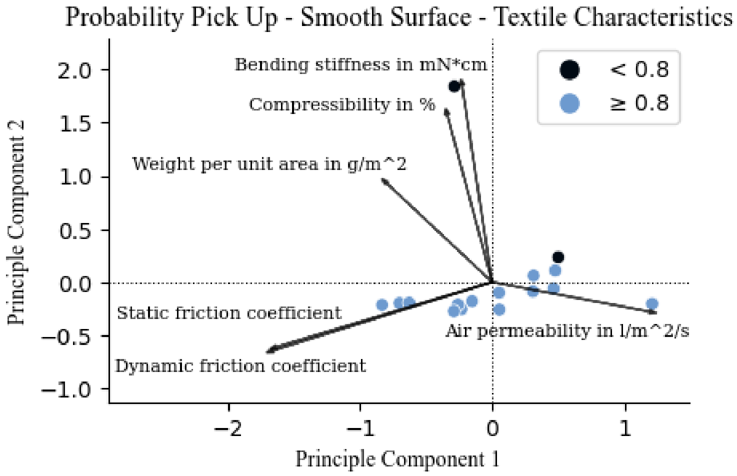


Fig. 5 PCA plot to show interrelationship of textile characteristics with the probability of a successful pick-up from a smooth surface.

The results of the PCA with the target being the pick up from a seat cover are very much alike that of the pick up from a smooth surface (Fig. 6).

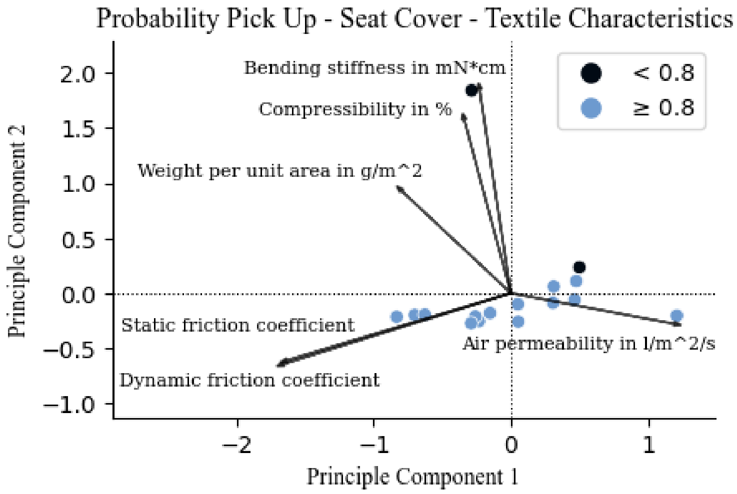


Fig. 6 PCA plot to show interrelationship of textile characteristics with the probability of a successful pick-up from a smooth surface.

Table 3. Pick-up probability and bending stiffness of the 16 materials.

Material name	Pick up probability – smooth surface	Pick up probability – seat cover	Bending stiffness (mN·cm)
PO1	0.0	0.0	124.79
PG1	1.0	1.0	2.16
PG2	0.8	1.0	2.60
R1	1.0	1.0	1.00
BU1	0.4	0.0	13.46
KG1	1.0	1.0	0.52
KG2	1.0	1.0	0.11
KG3	1.0	1.0	0.88
KG4	1.0	1.0	0.97
KG5	1.0	1.0	0.14
KG6	1.0	1.0	3.65
KG7	1.0	1.0	2.94
KG8	1.0	1.0	0.60
KG9	1.0	1.0	1.15

KG10	1.0	1.0	0.38
KG11	1.0	1.0	0.90

The ply separation from a smooth surface was plotted similarly to the pick-up tests with the probability being displayed as greater or equal and less than 0.8. As displayed in Fig. 7, only with material KG4 the plies could be separated reliably on a smooth surface.

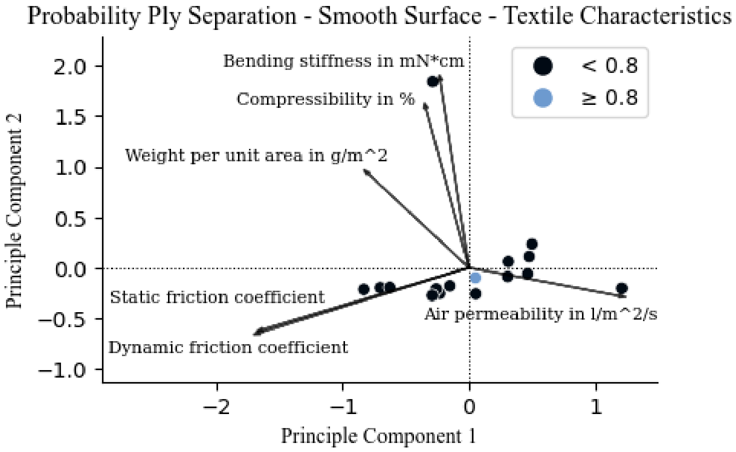


Fig. 7 PCA plot to show interrelationship of textile characteristics with the probability of a successful ply separation from a smooth surface.

The results of the ply separation test from a seat covered surface significantly differ from the ply separation test from a smooth surface (Fig. 8). While with seven materials the plies could be separated successfully, there does not seem to be a correlation to any specific textile characteristics that might have a positive or adverse impact.

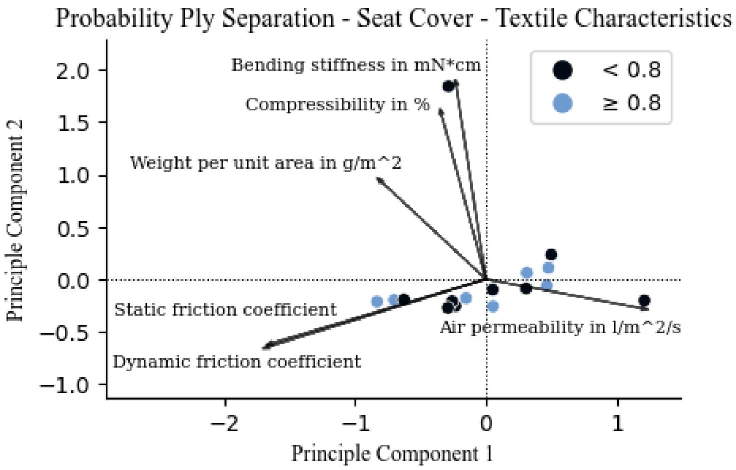


Fig. 8 PCA plot to show interrelationship of textile characteristics with the probability of a successful ply separation from a seat cover.

The PCA plot however does not show quantitative correlation. To discuss correlation quantitatively, the correlation coefficients of the textile characteristics and the gripper performance was determined (Table 4).

Table 4. Correlation coefficients of textile characteristics and gripper performance.

Ply separation: seat cover	Ply separation: smooth	Holding force (N)	Pick up: seat cover	Pick up: smooth surface	Dynamic friction coefficient	Static friction coefficient	Air permeability ($l/m^2/s$)	Compressibility (%)	Mass per unit area (g/m^2)	Bending stiffness (N*cm)	
-0.31	-0.10	0.40	-0.75	-0.89	-0.19	-0.16	-0.13	0.87	0.50	1.00	Bending stiffness (mN*cm)
0.07	-0.11	0.54	-0.51	-0.61	0.16	0.13	-0.35	0.14	1.00		Mass per unit area (g/m^2)
-0.37	0.03	0.40	-0.50	-0.65	-0.03	0.01	-0.14	1.00			Compressibility (%)
-0.20	-0.12	-0.45	0.18	0.18	-0.39	-0.35	1.00				Air permeability ($l/m^2/s$)
-0.03	0.12	0.60	0.39	0.25	0.99	1.00					Stat. friction coefficient
0.02	0.13	0.61	0.40	0.27	1.00						Dyn. friction coefficient
0.39	0.14	-0.28	0.95	1.00							Pick up: smooth surface
0.44	0.13	-0.05	1.00								Pick up: seat cover
0.16	-0.10	1.00									Holding force (N)
-0.09	1.00										Ply separation: smooth
1.00											Ply separation: seat cover

6 Discussion

Assessing the PCA plot without targets, as displayed in Fig. 3, a correlation between bending stiffness and compressibility can be observed. This was expected, as fabric thickness and density cause an increase in the geometric moment of inertia of the fabrics cross section, and thus the bending stiffness. This observation is further supported by a significant correlation of $r = 0.87$ (Table 4). As textile materials are soft materials, an increased thickness is likely to cause an increase in compressibility. A similar, though not as distinctive, connection can be observed between compressibility and mass per unit area. As compressibility is proportional to fabric thickness of soft materials, and an increase in thickness causes an increase in the mass per unit area, this is an intuitive correlation. As the materials in this study are from a variety of fibers with vastly different densities, it is not expected that there is a statistically significant correlation between bending stiffness, compressibility and mass per unit area. Further, it is noticeable that the friction coefficients and air permeability are located nearly opposite each other at a ~150° angle. This suggests that a low air permeability is likely to negatively correlate with high friction coefficients, though $r \sim 0.4$ does not suggest a statistically significant connection. As air permeability is facilitated by highly porous structures and thus less structured surface profiles, and surface structure facilitates high friction coefficients, a correlation is comprehensible.

During the targeted PCA using the holding force as a target, it was observed that the air permeability appears to have a significant impact on the holding force of a silicon finger gripper. Similar connection with the other gripper performance tests was not observed in the current investigation.

As the functionality of the finger gripper does not rely on air flow through the textile, and $r = -0.45$ shows no significant correlation, it can be assumed that this apparent correlation is due to the opposite location of the friction coefficient and air permeability in the plot. Thus, the correlation is likely to be between the holding force and static and dynamic friction coefficients and not the air permeability. This is further supported by the static friction coefficient being <1 for the materials with which the measured average holding force was < 2 N, and $r \sim 0.6$ (Table 4). While $r \sim 0.6$ is not statistically relevant, this is still valuable information and an indication to further investigate with a larger sample size, or to investigate the textile- textile friction behavior additionally to the textile-gripper friction coefficients.

The analysis shows a negative correlation of $r = -0.89$ between the bending stiffness and pick up performance (Fig. 5 and Table 4). This is expected, as an irregularly high bending stiffness is likely to impede the gripper folding to material into a grip. Further research is necessary to quantify the maximum bending stiffness in a material to reliably insure pick up.

The ply separation tests showed no definite connection to a specific characteristic or valuable. Further studies with a greater number of materials and samples are necessary to be able to provide a definite conclusion and to be able to quantify possible correlation.

The results of this study are only applicable to this gripper or structurally similar silicone grippers. The applicability of the obtained results to other type of finger grippers is to be investigated in future research. While the textile characteristics were measured in a climatic room with a temperature of 20 °C and a humidity of 65%, the gripper tests could not be conducted in a climatic room. To minimize the effect of temperature and humidity fluctuations, all gripper tests were conducted on the same day in the same room. Thus, the impact of environmental conditions on the textile characteristics and gripper performance could not be determined.

7 Summary

In this paper, the performance of a silicone finger gripper in picking up, holding and separating plies of textile materials was investigated. Sixteen textile materials of different applications, fabric types, materials and masses per unit area were included in this study to provide a comprehensive sample set.

The focus was set on evaluating the performance tests regarding correlation of gripper performance and certain textile characteristics, specifically the bending stiffness, compressibility, mass per unit area, static and dynamic friction coefficients and air permeability. It was found that low friction coefficients impair the holding force of the gripper. Further, a high bending stiffness has an adverse effect on the pick-up performance of the gripper. As the gripper folds the fabric into the grip, a high bending stiffness is likely to impair the folding in.

Further research is necessary to identify possible correlations between ply separation and textile characteristics, as these investigations were non-conclusive.

Acknowledgements

The testing of the mechanical properties of the textile samples was performed in the frame of the ZIM project CryoTec KK5090908CM1, which is part of the Central Innovation program for medium-sized companies from the Federal Ministry of Economics and Energy based on a resolution of the German Bundestag. Authors thanks all these institutions for providing the financial support. Authors thanks to Dr. Tino Kühn for the discussion during the test preparation.

Authors contribution

S. Herz: concept, methodology, data collection, analysis, writing, visualization; Y. Kyosev: methodology, editing, supervision, coordination. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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