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Reducing catheter advancement forces in PolyJet printed small vascular models for neurointerventional training through surface coatings

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Introduction: The fabrication of realistic additively manufactured small vascular models for neurointerventional training remains challenging, as current manufacturing technologies often require a compromise between geometric accuracy and realistic catheter handling. Although several additive manufacturing technologies have been investigated, many fail to reliably reproduce patent lumina in vessels smaller than 2 mm. PolyJet printing enables the fabrication of highly accurate vascular geometries with open lumina; however, it produces comparatively rough inner surfaces, resulting in increased friction and unrealistic catheter handling, thereby limiting the tribological realism of the models.
Methods: This study investigated whether surface coatings can improve the tribological performance of PolyJet vascular models while preserving their geometric accuracy. In this exploratory study, eight coating systems were evaluated using surface roughness measurements, cyclic catheter force measurements, short-term stability testing, micro-computed tomography, and clinical validation by experienced interventional neuroradiologists.
Results: Several coatings reduced surface roughness and catheter advancement forces compared with uncoated models. However, reduced roughness alone did not fully explain handling performance. Micro-computed tomography revealed substantial differences in coating homogeneity and lumen preservation, whereas force-path analyses demonstrated that homogeneous coatings produced smoother and more uniform force profiles. These objective findings were largely confirmed by the physicians' subjective assessments. Among the investigated systems, Teflon spray provided the best overall balance between friction reduction, coating homogeneity, ease of application, and clinical acceptance, whereas Aquasure achieved the lowest catheter advancement forces but required a substantially more complex coating procedure.
Discussion: The results demonstrate that targeted surface modification can overcome one of the major limitations of PolyJet printed small vascular models by improving tribological realism while preserving their geometric accuracy.

KEYWORDS
additive manufacturing, catheter handling, neurointerventional training, PolyJet printing, small vascular models, surface coatings, tribology

1 Introduction

Interventional neuroradiology has undergone rapid technological advancements in recent years. Significant progress in microcatheter, guidewire, and embolic material technologies has enabled endovascular procedures in vasculars with diameters below 2 mm, thereby extending treatment to increasingly complex and fragile cerebrovascular anatomies (Haldrup et al., 2020; Saver et al., 2020). Concurrently, novel therapeutic procedures have been developed, including embolization for the targeted occlusion of pathological or therapeutically significant vascular structures using particles, coils, or liquid embolization agents (Haldrup et al., 2020; Sila et al., 2023). Clinically relevant examples include embolization of the middle meningeal artery (MMA) for the treatment of chronic subdural hematoma (cSDH) and interventional therapy for arteriovenous malformation (AVM) (van Rooij et al., 2012; Haldrup et al., 2020; Pinkiewicz et al., 2022; Sila et al., 2023). Neurointerventions imposes considerable demands on the technical proficiency and haptic understanding of the neurointerventional physicians, particularly in circumstances involving fragile small vasculars and microinstruments.

In this context, there is an increasing demand for the use of realistic simulators in the training and continuing education of physicians engaged in neurointerventions. The objective of these models is to facilitate the training of interventional techniques in a manner that is standardized, reproducible, and risk-free training environment before clinical application, thereby minimizing the risk to patients. A variety of simulators can be used for neurointerventional training purposes. While the utilization of animal models facilitates the employment of original instruments in biological tissue, they are concomitantly associated with considerable ethical, logistical and financial constraints (Nawka et al., 2020; Arturo Larco et al., 2023; Mokin et al., 2024). Furthermore, the vascular anatomy of animal models differs significantly from human cerebrovascular anatomy, particularly in the region of small intracranial vasculars. By contrast, virtual simulation systems permit a substantial degree of variability and repeatability in the scenarios. A range of pathological constellations, vascular courses and difficulty levels can be simulated with a high degree of flexibility and used to guide specific training. However, to date, the depiction of the mechanical interaction between the catheter, guidewire, and vascular wall has been limited in its realism, as the physical material properties of the instruments and vascular structures are only approximated through modelling (Rudarakanchana et al., 2014; Nesbitt et al., 2016; Latham et al., 2019). Furthermore, the employment of simplified or standardized input devices instead of original neurointerventional instruments as substitutes for the original neurointerventional instruments has been observed, which further limits the transferability to clinical practice (Nesbitt et al., 2016). Physical vascular models are increasingly being used in interventional neuroradiology for training and research purposes because they enable the use of real neurointerventional instruments in a realistic angiography suite (Madjidyar et al., 2015; Russ et al., 2015; Pfau et al., 2018; Schmiech et al., 2025). These models enable practical simulation of endovascular procedures under controlled and reproducible conditions, and are an important addition to virtual simulation systems, particularly for training in complex catheter and wire manoeuvres. However, previous studies have shown that fabricating physical small vascular models for neurointerventional applications remains technically challenging, particularly in terms of manufacturing free cavities and realistically reproducing catheter–vascular interactions (Ionita et al., 2014; Ayabe et al., 2021; Bisighini et al., 2022; Sobirey et al., 2025). In addition to geometric accuracy, the tribological properties of the inner vascular surface are a key factor in determining the realism of physical vascular models. These include surface roughness and the friction behaviour resulting from contact between instruments and the vascular model wall. Both geometric mapping and tribological properties are crucial for the realistic simulation of small vascular model, significantly influencing navigability and perceived haptics.

In a preliminary study conducted by our research group, we investigated the suitability of various additive manufacturing processes and materials for producing models of microvascular neurovascular structures (Sobirey et al., 2025). Our focus was on the reproducible fabrication of open cavities with small vascular diameters, as well as the fundamental suitability of the models for interventional training applications. We found that models produced using stereolithography (SLA) had significant limitations in terms of the patency and reproducibility of small vascular lumens (Sobirey et al., 2025). By contrast, Polyjet models reliably reproduced complex vascular geometries and open lumens of the MMA (Sobirey et al., 2025). However, interventional physicians rated these models as significantly too rough in terms of their haptic properties during practical evaluation, which limited the realism of catheter navigation (Sobirey et al., 2025).

As reported in previous studies, increased friction forces and difficulties in navigating catheters through vascular models have been observed (Kim et al., 2022; Rivera et al., 2023). Sadasivan et al. and Madjidyar et al. investigated friction-reducing coatings (Madjidyar et al., 2015; Sadasivan et al., 2024). However, these were either not applied to small vascular structures or were evaluated exclusively in silicone models without specifying the material or manufacturing process. Furthermore, these studies did not include objective quantitative analyses of friction reduction, nor were the coatings validated by experienced users regarding a subjective improvement in handling.

A variety of test benches for investigating the tribological properties between catheters and vascular models have been documented in the literature. Takashima et al. utilised experimental methods and numerical simulations to examine the interaction between a catheter and a guidewire within a vascular model. The model employed was a simplified one with a large lumen, without consideration of physiological boundary conditions such as blood flow pulsatility (Takashuima et al., 2017). Klink et al. presented another test, but their experimental design was overly simplified and did not adequately replicate the physiological conditions of the human vascular system (Klink et al., 2021). In their study, Kuhl et al. compared the friction properties of additively manufactured vascular models (Stereolithography process) with biological vasculars of animal origin (Kuhl et al., 2022). Pulling tests were conducted in simplified vascular geometries (Kuhl et al., 2022). However, the insertion and navigation processes of the instrument under clinically relevant conditions were not investigated. To date, systematic studies on friction-reducing surface coatings in PolyJet based neurovascular small vascular models under realistic pressure- and advancement-based loading conditions are lacking. In particular, clinically relevant insertion and navigation movements in complex small vascular geometries have not been quantitatively assessed using standardized methods, nor have such coatings been evaluated through a combination of objective force measurements and validation by experienced users.

This study aims to optimize the interaction between catheters and additively manufactured MMA models for interventional neuroradiology. The objective was not to reproduce the exact tribological properties of native cerebral vessels, but rather to reduce the unrealistically high catheter advancement forces of additively manufactured vascular models. As there are currently no quantitative reference values available for catheter advancement forces in human cerebral vessels, an objective target force cannot be defined. Thus, we compared different surface coatings and blood-mimicking fluids (BMF) experimentally and complemented the results with a clinical evaluation performed by experienced interventional neuroradiologists. Various surface coatings and BMF are being investigated for their influence on the tribological properties of the models. In order to enable an objective evaluation, a test bench will first be developed to quantitatively measure the catheter advancement forces between the microcatheter and the vascular model. Subsequently, experienced neurointerventionalists will evaluate the coatings under investigation with regard to haptics, navigability, and realistic training characteristics in the HANNES (Hamburg ANatomical NEurointerventional Simulator) simulation model. The HANNES simulator is currently used to simulate interventional neuroradiological procedures, including the treatment of aneurysms, strokes, and vascular stenoses (Schmiech et al., 2025). It is based on a detailed 3D-printed (stereolithography) model of the arterial tree, which replicates the course of the vasculars from the groin to the head (Schmiech et al., 2025). By using original treatment instruments in a realistic angiography environment alongside an integrated fluid system that simulates physiological blood flow conditions, the simulator is able to provide clinically relevant and reproducible training scenarios (Schmiech et al., 2025).

2 Materials and methods

The coated MMA model for the endovascular treatment of cSDH was developed through close collaboration between physicians and engineers. The aim was to create a model that replicated the anatomical conditions and haptic characteristics of neurointerventional procedures as accurately as possible. To achieve this, medical expertise was combined with technical know-how. Development of the coated MMA model was guided by VDI guideline 2221 on the development of technical products and systems, encompassing the planning, conceptualisation, design and development phases (VDI, 2019). Initially, the requirements for the coating were analysed and documented in the form of a requirements list. Particular emphasis was placed on functional and material-specific requirements for the coating. The coating was intended to reliably reduce the internal roughness caused by the PolyJet process, while also depositing evenly within the narrow vascular lumens without causing a major change to the inner diameter of the vascular models. Additionally, the coating had to be resistant to the BMF used and the PolyJet material should not react with the applied liquids. Moreover, the coating should not peel off or crack during use or exposure to liquids. Furthermore, the use of non-toxic materials and the simplest possible disposal process were considered. In addition to these functional properties, manufacturing requirements were also defined. The objective was to develop a cost-effective, user-friendly, fast-curing coating solution that could easily be integrated into existing manufacturing processes.

2.1 Selection of coatings and blood-mimicking fluid

Following the definition of requirements, the conceptual design phase is initiated in accordance with VDI 2221 (VDI, 2019). In this step, a functional structure is developed that maps both the main and sub-functions of the system. It serves as the basis for identifying suitable functional principles for the individual sub-functions and for systematically structuring the design process. The Morphological Box was utilized to formulate sub-solutions within the functional structure. This methodology facilitates a systematic decomposition of the problem, thereby enabling the generation of a range of solution approaches. On this basis, several alternative concepts were developed, which were then subjected to a comparative analysis using a weighted evaluation system. A technical and economic evaluation was conducted on the coatings and BMF utilized. In the course of the evaluation process, a range of factors were given full consideration. Among these were technical criteria, such as friction reduction, as well as economic aspects, such as material costs. The highest-rated solution approaches were then selected and investigated further.

The present study investigates the utilisation of tap water, tap water-glycerin (Glycerin (99.5%) Doktor-Klaus, FloraCura GmbH, Garmisch-Partenkirchen, Germany) mixture, and tap water with added baby shampoo (PENATEN Shampoo by Johnson & Johnson GmbH, Neuss, Germany). The objective of this study was to investigate the effect of different liquids on the friction and sliding behaviour between the vascular model and neurointerventional instruments. Compared to blood, which has a dynamic viscosity of approximately 3.5–4.5 mPa·s at 37 °C (Oglat, 2022), water has a considerably lower dynamic viscosity of approximately 0.69 mPa·s at 37 °C (Mudie et al., 2010). Therefore, glycerin was added to increase the viscosity of the water. Water–glycerin mixtures are widely used as BMF because their viscosity can be adjusted over a broad range depending on the mixing ratio (Completo et al., 2014; Luisi et al., 2023). In contrast, only a small amount of baby shampoo was added to water, so no significant increase in viscosity was anticipated. However, the surfactants in the shampoo reduce surface tension and improve the wettability of hydrophilic coating systems, thereby influencing the sliding behavior. The present study investigates the influence of different BMF on the tribological behaviour of the training model.

In order to investigate the influence of different surface modifications on haptics in the vascular model, a range of coating systems with varying tribological and surface chemical properties were utilised. From a functional perspective, these can be categorised into three distinct groups: elastic coatings, static- and sliding-friction-reducing coatings, and hydrophilic or hydrogel-like coatings. These coating classes rely on different tribological

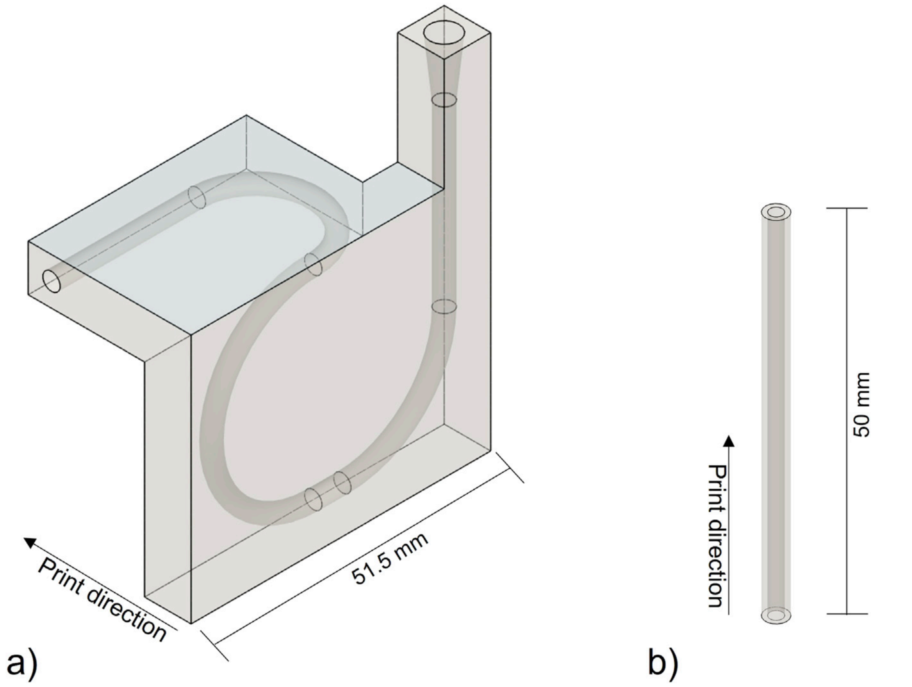

FIGURE 1
Design of the sample used in this study **(a)** cylindrical channel with the course of the foramen spinosum for tribological investigations and **(b)** hollow cylinder for coating analysis by µCT.

mechanisms, including modification of surface compliance, reduction of surface energy and adhesion, or the formation of hydrated boundary layers. The present study examined the use of Plasti Dip (Plasti Dip Europe GmbH, Schwerin, Germany) and RT 601 (Wacker Chemie AG, München, Germany) as elastic base coatings. Plasti Dip is a solvent-based synthetic rubber coating that forms a flexible polymer film layer after the solvent evaporates. RT 601 is an addition-curing silicone elastomer that cures to form an elastic silicone rubber. The primary function of elastic coatings is to modify the mechanical interaction between the catheter and the vessel wall. The formation of a compliant polymer layer serves to smoothen the printed layer structure, while also effecting modifications to both surface compliance and contact characteristics. For the investigation on the reduction of static and sliding friction, the focus was on the following substances: Hard Coat Finish (HCF) (Plasti Dip UK Limited, Liphook, United Kingdom.), Aquasure (Aquasure (Gear Aid, Bellingham, WA, United States), silicone oil (Ballistol, F.W. Klever GmbH, Aham, Germany) and Teflon spray (Ballistol, F.W. Klever GmbH, Aham, Germany). Following the curing process, HCF forms a smooth, durable polymer surface. Aquasure creates a flexible polyurethane layer. Silicone oil functions as a lubricating film, reducing surface energy, while Teflon spray forms a solid, highly low-friction sliding layer. HCF and Aquasure reduce friction primarily by forming smooth, continuous polymer surfaces that minimize surface asperities, whereas silicone oil acts as a lubricating boundary film and PTFE-based Teflon spray provides a low-surface-energy sliding layer that reduces adhesive friction. X-tec HP3066 (X-tec) (NANO-X GmbH, Saarbrücken-Güdingen, Germany) is regarded as a hydrophilic system and is a water-based coating system with extremely high hydrophilicity and contact angles of less than 10°, which improves wettability. Hydrophilic coatings reduce friction by retaining water at the surface, thereby forming a hydrated boundary layer that minimizes direct solid-solid contact during catheter advancement.

2.2 Sample geometry and manufacturing

The sample developed for the investigation of catheter advancement forces on the test bench consists of a cylindrical channel with a constant circular cross-section and a diameter of 2 mm, which follows the anatomical course of the foramen spinosum of the MMA. Patient-specific diameter variations were deliberately abstracted to achieve an experimentally reproducible geometry. The surrounding specimen body was reduced to the functionally relevant areas, resulting in a compact, material- and cost-efficient test specimen for tribological investigations in an endovascular context. For the purpose of analysing coating thickness and distribution, a straightforward hollow cylinder measuring 1.75 mm in diameter with a wall thickness of 0.625 mm was examined using micro-computed tomography (µCT). The design of the samples is illustrated in Figure 1.

The MMA previously described by Sobirey et al. was used for the subsequent testing of the coatings' handling properties and for application testing with the physicians (Sobirey et al., 2025). The samples were fabricated using the PolyJet process with an Agilista 3200W from Keyence (KEYENCE Corporation, Osaka, Japan) using the material AR-G1H. The post-processing of the samples to remove the support material from the cavities was performed using an ultrasonic bath and manual flushing with a syringe.

TABLE 1 Overview of coating application and associated curing times and temperature (RT-room temperature).

Coating	Application	Application time	Curing time	Curing temperature
Plasti dip	Plasti dip: Thinner (3:1); syringe filling and draining of the lumen; manual rotation; 3 coats	10 min	4 h	RT
RT 601	Component A:B (9:1); syringe filling and draining of the lumen; manual rotation; 1 coat	10 min	10 min	100 °C
HCF	Syringe filling and draining of the lumen; manual rotation; 2 coats	10 min	4 h	RT
Aquasure	Aquasure: Curing agent (3:1); syringe filling and draining of the lumen; manual rotation; 1 coat	10 min	2–4 h	RT
Silicone oil	Spray coating into the lumen; 1 coat	<10 s	-	RT
Teflon spray	Spray coating into the lumen; 1 coat	<10 s	60 s	RT
X-tec	Syringe filling and draining of the lumen; manual rotation; 1 coat	1 min	15 min	80 °C

2.3 Coating process and preparation of BMF

Prior to the coating process, all samples were subjected to a thorough cleaning procedure involving an ultrasonic bath, followed by rinsing with isopropanol (IPA) and drying to ensure the removal of any residual contaminants. Samples intended for Plasti Dip and HCF coatings were additionally pretreated with a primer (Mipa 1K, MIPA SE, Essenbach, Germany) to improve coating adhesion. The primer-coated samples were subsequently tempered at 60 °C for 60 min and allowed to dry for 10 min before the coating procedure. Teflon spray and silicone oil were applied by spray coating directly into the vascular lumen to achieve complete coverage of the inner surface. The remaining coatings were applied using a 20 mL disposable syringe by filling and subsequently draining the vascular lumen. The samples were slowly rotated manually to ensure a homogeneous distribution of the coating along the entire lumen before the excess coating material was drained. All coatings were applied in a single coat, except for Plasti Dip (three coats) and HCF (two coats). For multilayer coatings, each layer was allowed to cure according to the respective curing conditions before the subsequent layer was applied. Table 1 provides an overview of the coating application methods and curing conditions.

In addition to coating the lumens of the models, the outer surface of the sample was coated to establish the initial impact on roughness, as measured by a surface profilometer. For this purpose, the coatings were applied with a brush.

The BMF used in this study consisted of water, water containing 0.6 vol% baby shampoo, and a 30 vol% glycerin-water mixture. A total of 10 L of each BMF was prepared on a hot plate equipped with a magnetic stirrer. The water was heated to approximately 40 °C–50 °C, and the components were mixed under continuous stirring until homogeneous solutions without visible inhomogeneities were formed. Subsequently, experiments were conducted at a temperature of 37 °C.

2.4 Test bench setup

The conceptual approach of the test bench is based on the targeted abstraction of the real endovascular situations. While simulations in HANNES allow for a high degree of realism, their reproducibility is limited due to numerous influencing factors. The developed test bench was therefore designed as a fundamental experiment in which the clinical situation is reduced to the physically relevant tribological interactions. The focus of this study is the relative motion of a wire inside a catheter in contact with an additively manufactured specimen under pulsatile fluid flow. The geometry is designed to ensure constant contact between the wire and the channel wall, resulting in continuous friction-related effects. The specimen is connected to the HANNES fluid system and is continuously flushed with a BMF, thereby simulating tribological conditions under physiological conditions. The wire is clamped in a universal testing machine (GALDABINI QUASAR 100, Galdabini SPA, Cardano al Campo, Italy) that generates cyclic forward and backward movements at a constant speed. Additionally, the stationary catheter was continuously flushed with a saline solution, similar to clinical neurointerventional procedures. The BMF circulates through the vascular model while the saline solution is used exclusively for flushing the catheter. This setup enables the measurement of catheter advancement forces generated by the interaction between the guidewire, catheter, BMF, and vascular model. Figure 2a shows a schematic representation of the test bench, while Figure 2b illustrates a section of the experimental setup.

The measurement of force is accomplished through the utilisation of a KD24s 10 N force sensor (ME-Meßsysteme GmbH, Hennigsdorf, Germany; accuracy class 0.1, corresponding to ±0.01 N full-scale accuracy). The acquisition and analysis of data is performed using an MX840 signal conditioner and catmanEasy-A software (HBM GmbH, Darmstadt, Germany) at a sampling rate of 100 Hz. The geometry of the sample is designed to be approximately 2 mm in diameter, with the aim of accommodating robust and cost-effective catheter and guidewire systems. The procedure involved the utilisation of a Catalyst 5 F catheter (Stryker Neurovascular, Portage, MI, United States) with an outer diameter ranging from 1.76 to 1.86 mm, in conjunction with a Merit Stiff wire (Merit Medical Systems, South Jordan, UT, United States) with a diameter of 0.89 mm.

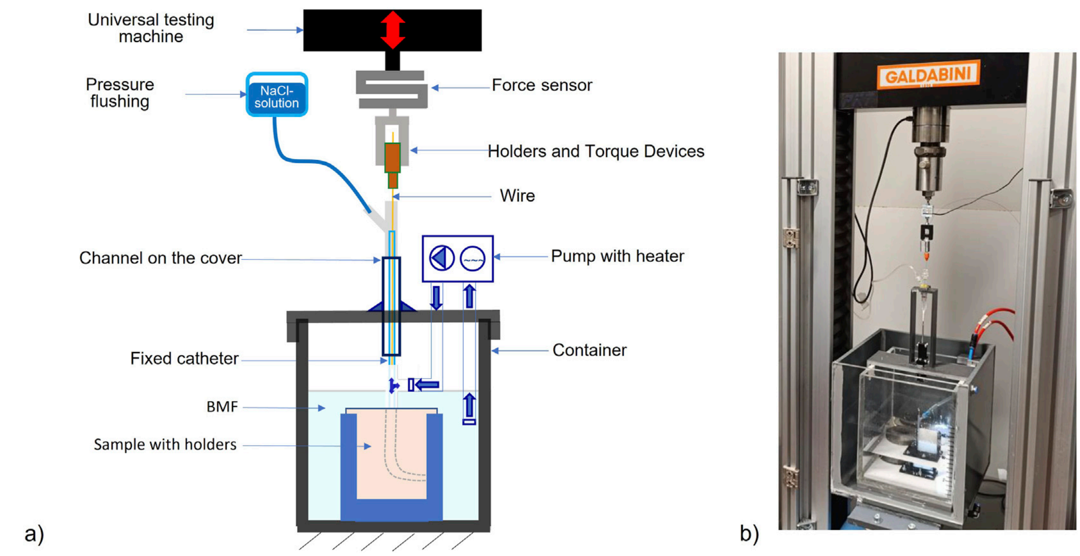

FIGURE 2
Test bench setup based on a reduced endovascular model focusing on tribological interactions, where **(a)** shows a schematic representation of the test bench, while **(b)** illustrates a section of the experimental setup.

2.5 Analysis and interpretation of the measured data

The study examined the impact of coatings on haptic properties in the training model, with a focus on friction reduction, short-term stability, homogeneous coating, ease of application, and cost.

2.5.1 Roughness

A preliminary screening was performed to evaluate whether the different coating systems altered the surface profile after application. As the tribologically relevant inner lumen could not be assessed using the available roughness measurement system, the measurements were instead carried out on the coated outer surface. This approach served solely as an initial comparison of the coating-induced changes in surface topography. The assessment entailed the measurement of surface roughness utilizing the MarSurf UD 120 roughness and contour measuring machine (Mahr GmbH, Göttingen, Germany). To this end, three roughness measurements (tolerance 0.1 µm) were taken at different locations on the sample, each with a scanning distance of 9.97 mm. The roughness measurements were performed transverse to the layer lines and orthogonal to the print direction. The parameters R_a (arithmetic mean roughness), R_q (root mean square roughness), R_z (mean roughness depth), and R_{max} (maximum roughness depth) are used to evaluate roughness. The coating thickness was assessed separately using µ-CT, as described in the following section.

2.5.2 Force measurement and short-term stability

Cyclic force measurements were performed to evaluate the friction properties of the coating systems under investigation. In this experimental series, analysis is confined to the advancing forces, given that haptic perception in clinical use principally occurs during this phase. The contact and catheter advancement forces that arise during this process determine the tactile feedback and, consequently, the subjective assessment of the vascular haptics. To quantitatively characterize the data, the global median (GMed), the mean-of-means (MoM), and the global maximum (GMax) were determined. The global median was employed as the principal metric to delineate the prevailing catheter advancement force level. The global maximum was used as an additional parameter to identify pronounced force peaks within each advancement cycle. The mean-of-means method enables an equally weighted evaluation of the catheter advancement force level across all measurement cycles. The investigations were conducted with a sample size of N = 1. The limited number of samples was due to the restricted availability of the instruments used. The test procedure entails the movement of the testing machine in a back-and-forth motion over a stroke length of 40 mm at regular intervals. This motion is executed at a constant feed rate of 1 mm per second and a cycle time of 40 s. The BMF is maintained at a temperature of 37 °C throughout the experiment. Catheter advancement forces for the comparison of coating systems were determined from a measurement series comprising 20 cycles. Short-term functional stability was assessed separately using an independent measurement series consisting of 60 consecutive sliding cycles in baby shampoo. The recorded catheter advancement force represents the total force needed to navigate the catheter through the entire experimental setup, which includes the vascular model, coating, BMF, catheter, and guidewire. Therefore, catheter advancement force was the primary outcome measure used to compare the investigated coating systems under standardized experimental conditions.

2.5.3 Coating handling and costs

A comparative analysis was conducted of the coating systems in terms of cost and application. To facilitate comparison, material costs were normalized to 100 mL. For sprays (silicone oil, Teflon spray), the value of this presentation is limited, as the applied quantity cannot be reliably quantified due to the aerosol-based application method and typically results in significantly thinner film thicknesses. Furthermore, the application-related criteria, including ease of use and the quality of the free cavities, were assessed qualitatively.

2.5.4 Micro-computed tomography

The quantification of coating thicknesses and the resulting changes in internal geometry were achieved through the examination of the samples using µCT (µCT 35, SCANCO Medical, Brüttisellen, Switzerland). The objective of this study was to evaluate the homogeneity of the coating and the subsequent alterations in lumen diameter. For the uncoated reference samples, the number of replicates (n) was set at three to ascertain the print variation, while a single sample was examined for each coating system. To ensure sufficient spatial resolution of the coatings, the µCT scan was limited to a 20 mm long central section of the cylindrical samples. The measurements were conducted utilising a tube voltage of 70 kVp, a tube current of 114 µA, and a power of 8 W. The reconstructed data sets boast a resolution of 74 µm. The reconstruction was performed in DICOM format and exported for further processing. The data segmentation was executed using 3D Slicer (Slicer Community, Brigham and Women's Hospital, Boston, United States). The outer sample contour was separated from the background using a threshold-based segmentation technique with a threshold range of 800–2243 HU and subsequently exported as a surface model. The resulting model was then processed in Autodesk Meshmixer (Autodesk Inc., San Rafael, United States) to isolate the interior (lumen) and extract it as an STL file. The geometric analysis was executed in the MATLAB environment (MathWorks Inc., Natick, United States). The mean, minimum, and maximum diameters, as well as the standard deviation, were calculated. Furthermore, a spatial diameter distribution, or heatmap, was determined, as well as the diameter profile.

2.5.5 Application test

A final evaluation of the coatings selected in the preliminary studies and the BMF used was conducted through experimental investigation performed by two interventional neuroradiologists with 10 and 13 years of experience in their respective fields. The coated MMA models were connected to the carotid artery of the HANNES simulator using the edgeless connectors. The simulator was operated under standardized physiological conditions at 37 °C with pulsatile flow, a pulse rate of 60 beats per minute, and a pressure ranging from 70 to 120 mmHg. These operating parameters were kept constant throughout all experiments to ensure comparability between the investigated coating systems. The experiments were conducted in a realistic angiography suite utilising standard clinical instruments. In order to simulate SDH treatment, the Marathon™ microcatheter (Medtronic, Dublin, Ireland) and the Traxcess Guidewire 14 (Terumo Neuro, Tokyo, Japan) were navigated transfemorally through the vascular tree of HANNES into the respective MMA. For the purpose of examining additional models, the catheter was withdrawn to the carotid artery and then advanced once more. The probing ability and flow were evaluated using digital subtraction angiography (DSA) following the injection of a contrast agent. In order to avoid any potential influence on the results, the physicians were required to refrain from any visual or tactile contact with the models prior to the initiation of the study. Following a thorough examination of each model, the defined evaluation criteria were assessed using a questionnaire on a five-point Likert scale ranging from 1 (very poor) to 5 (very good). The list of questions is provided below.

TABLE 2 Results of the roughness for the different coatings on the samples, noting the values R_a, R_q, R_z and R_max. The examination was carried out transverse to the layer lines and orthogonal to the print direction.

Coating	R_a [µm]	R_q [µm]	R_z [µm]	R_max [µm]
Uncoated	11.5	14.2	64.1	106.4
Plasti dip	2.4	3.0	13.6	16.7
RT 601	0.2	0.3	1.7	3.2
HCF	5.5	7.6	36.3	64.1
Aquasure	2.2	3.4	16.6	39.3
Silicone oil	9.1	11.2	52.6	64.6
Teflon spray	5.8	7.4	30.3	46.7
X-tec	2.9	4.2	19.4	28.2

- Is the overall feel of the model realistic compared to a human MMA?
- Is the probing of the model realistic compared to a human MMA?
- The friction between the instrument and the vessel wall is realistic.
- The resistance is realistic.
- Stick-slip effects frequently occur during probing.
- The stick-slip effects that occur are very noticeable.

3 Results

This chapter presents the findings from the experimental study evaluating the coating systems under investigation. First, the results of the roughness and force measurements are presented. Subsequent to this, an evaluation of the coatings is conducted in terms of their handling and costs. Subsequent to this, the results of the µCT analysis are presented. Finally, the experimental results are compared with the evaluations provided by the physicians.

3.1 Roughness

The roughness measurements were performed as a preliminary screening to assess coating-induced changes in surface topography and should therefore not be interpreted as a direct representation of

TABLE 3 Summary of catheter advancement force values (GMed, MoM, and Gmax) for the coatings tested in the BMF water (W), baby shampoo (BS), and glycerin (G).

Coating	GMed [N] W	GMed [N] BS	GMed [N] G	MoM [N] W	MoM [N] BS	MoM [N] G	Gmax [N] W	Gmax [N] BS	Gmax [N] G
Uncoated	0.18	0.13	0.22	0.19	0.14	0.24	0.37	0.37	0.48
Plasti dip	0.04	0.05	0.21	0.07	0.06	0.22	0.20	0.16	0.35
RT 601	0.10	0.06	0.06	0.12	0.06	0.07	0.26	0.09	0.19
HCF	0.08	0.07	0.06	0.10	0.08	0.07	0.22	0.16	0.15
Aquasure	0.05	0.04	0.07	0.07	0.05	0.08	0.31	0.18	0.18
Silicone oil	0.07	0.10	0.14	0.09	0.11	0.16	0.22	0.19	0.27
Teflon spray	0.05	0.05	0.16	0.06	0.05	0.17	0.14	0.15	0.29
X-tec HP3066	0.07	0.07	0.11	0.10	0.08	0.15	0.26	0.20	0.33

the tribologically relevant inner lumen surface. The roughness parameters R_a, R_q, R_z, and R_max were used to compare the surface topography of the coated specimens. Since these parameters characterize different aspects of surface topography, multiple metrics were considered. R_a and R_q describe average surface roughness, while R_z and R_(max) provide information about local peaks and valleys that may affect tribological performance. Table 2 summarizes the mean values obtained from three measurements on a single sample. The uncoated surface served as the reference. The roughness measurements indicate that several coating systems reduce surface roughness compared to the uncoated reference. The most pronounced reductions are observed for the Aquasure, Plasti Dip, and RT 601 coatings.

3.2 Force measurement and short-term stability

The cyclic force measurements demonstrate a marked influence of both the surface coating and the BMF utilised on the friction behaviour (see Table 3). In comparison with the uncoated reference sample, all of the tested coatings were found to be capable of reducing the catheter advancement forces. However, the extent of this reduction was found to vary depending on the specific medium.

In water, the lowest median values for feed force were achieved with Plasti Dip (0.04 N) and Teflon spray (0.05 N). Furthermore, notable decreases in catheter advancement forces were observed for Aquasure (0.05 N), HCF (0.08 N), X-tec (0.07 N), and RT 601 (0.10 N) in comparison to the uncoated sample (0.18 N). The lowest overall catheter advancement forcess were measured in the case of baby shampoo, among the three tested media. The lowest global median values were measured for Aquasure (0.04 N), Plasti Dip (0.05 N), and Teflon spray (0.05 N). Concurrently, the maximum forces exerted by these coatings were found to be considerably lower than those of the uncoated reference sample (0.37 N). However, a divergent pattern emerged in the glycerin sample. While RT 601 and HCF continued to exhibit low catheter advancement forces with global median values of 0.06 N each, Plasti Dip (0.21 N) and Teflon spray (0.16 N) achieved higher values. Furthermore, it was observed that higher maximum forces were measured, with the uncoated sample reaching the highest value of all the tested combinations at 0.48 N. Overall, baby shampoo demonstrated a combination of low catheter advancement forces and clear differentiation between the investigated coating systems. In contrast, glycerin exhibited stronger coating-dependent behavior and higher force values in some cases. The differences between the BMF are illustrated in Figure 3 using representative force-time curves from three of the total 20 measurement cycles of a sample coated with Teflon spray.

While the force curves of baby shampoo and water exhibit similarity, with low catheter advancement forces and a smooth curve profile, the measurement in glycerin demonstrates greater fluctuations throughout the entire cycle. Furthermore, the measured forces are at a higher level than those in the other two media. It should be noted that the experiments were conducted with n = 1 due to the limited availability of the instruments. Consequently, the uncoated reference sample was remeasured following the completion of all measurements. This served to verify possible wear effects and to estimate measurement fluctuations. No relevant differences were observed in comparison to the initial reference measurement. Based on these findings, baby shampoo was chosen as the standard BMF for subsequent investigations due to its combination of low catheter advancement forces and clear differentiation between the investigated coating systems.

Figure 4 presents the representative force-time curves for selected coatings in baby shampoo, compared to the uncoated reference sample. Irrespective of the coating employed, lower force levels were observed in comparison to the reference. Teflon spray and Plasti Dip, in particular, demonstrate uniform force curves with only a few pronounced peaks. Aquasure and HCF also exhibit reduced catheter advancement forces, but their curves are less uniform. Aquasure demonstrated the lowest catheter advancement force of all the coatings that were tested in baby shampoo, with a global median of 0.04 N. Despite this low median force, the force profile of Aquasure exhibited more pronounced local fluctuations than those of Teflon spray and Plasti Dip. In general, the force-time curves in baby shampoo manifest as being more uniform and exhibiting fewer pronounced peaks in comparison to the corresponding measurements in glycerin. Concurrently, the distinctions between the discrete coating systems become more distinctly apparent.

In order to provide a more detailed characterisation of the friction behaviour, the measurement data were subjected to

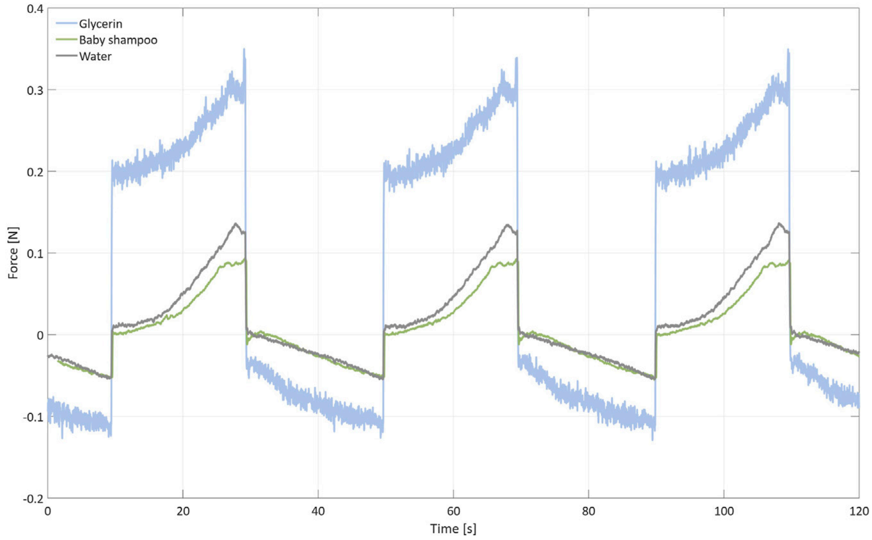

FIGURE 3
Exemplary representation of three of the 20 recorded force cycles of a Teflon spray-coated sample in water, baby shampoo, and glycerin.

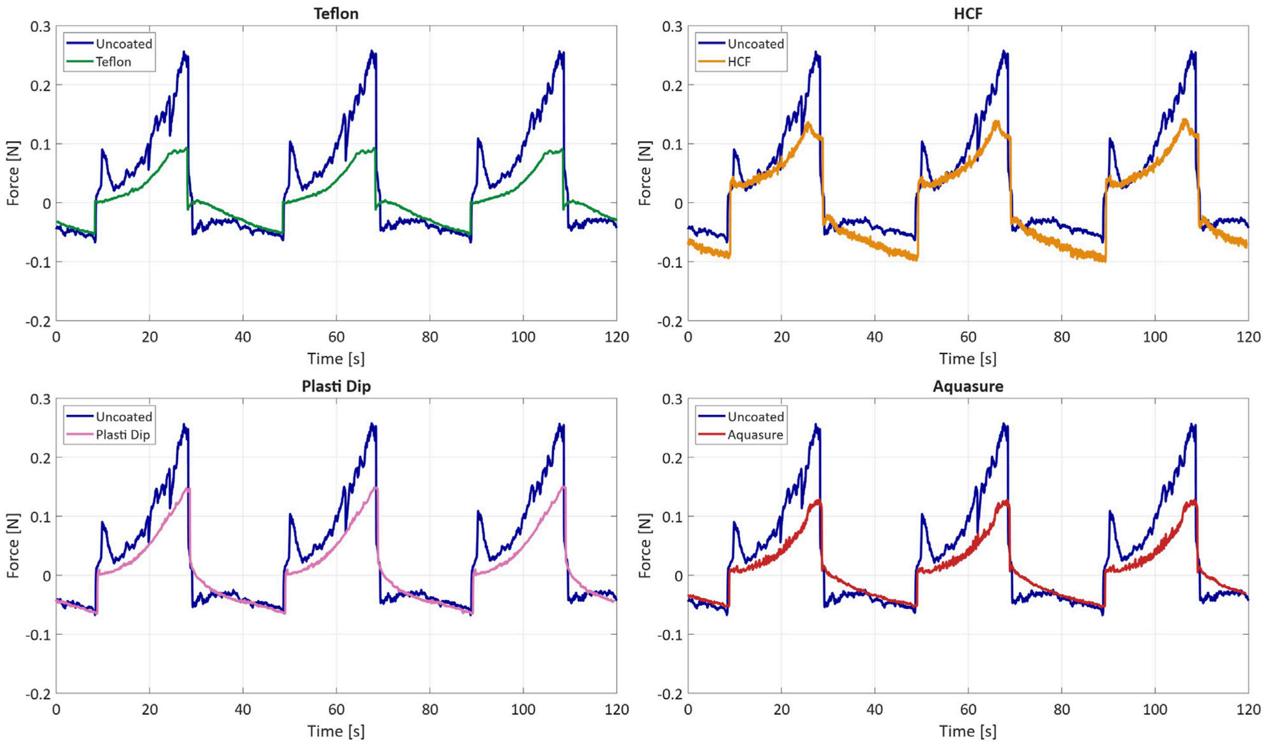

FIGURE 4
Exemplary force–time curves of selected coatings (Teflon spray, HCF, Plasti Dip, and Aquasure) in the BMF baby shampoo compared to the uncoated reference sample.

additional analysis in the form of force-displacement curves (see Figure 5). To this end, the mean curve from three representative measurement cycles was plotted for each case. For the sake of clarity, the Teflon spray, Plasti Dip, Aquasure, and HCF coatings are presented as illustrative examples. The force-displacement diagrams illustrate the differences in force trends along the path of motion. It is evident that Teflon spray and Plasti Dip demonstrate the lowest force levels in addition to the most uniform trends, exhibiting only a few pronounced peaks. Aquasure also exhibits reduced catheter advancement forces, but the force trend is less

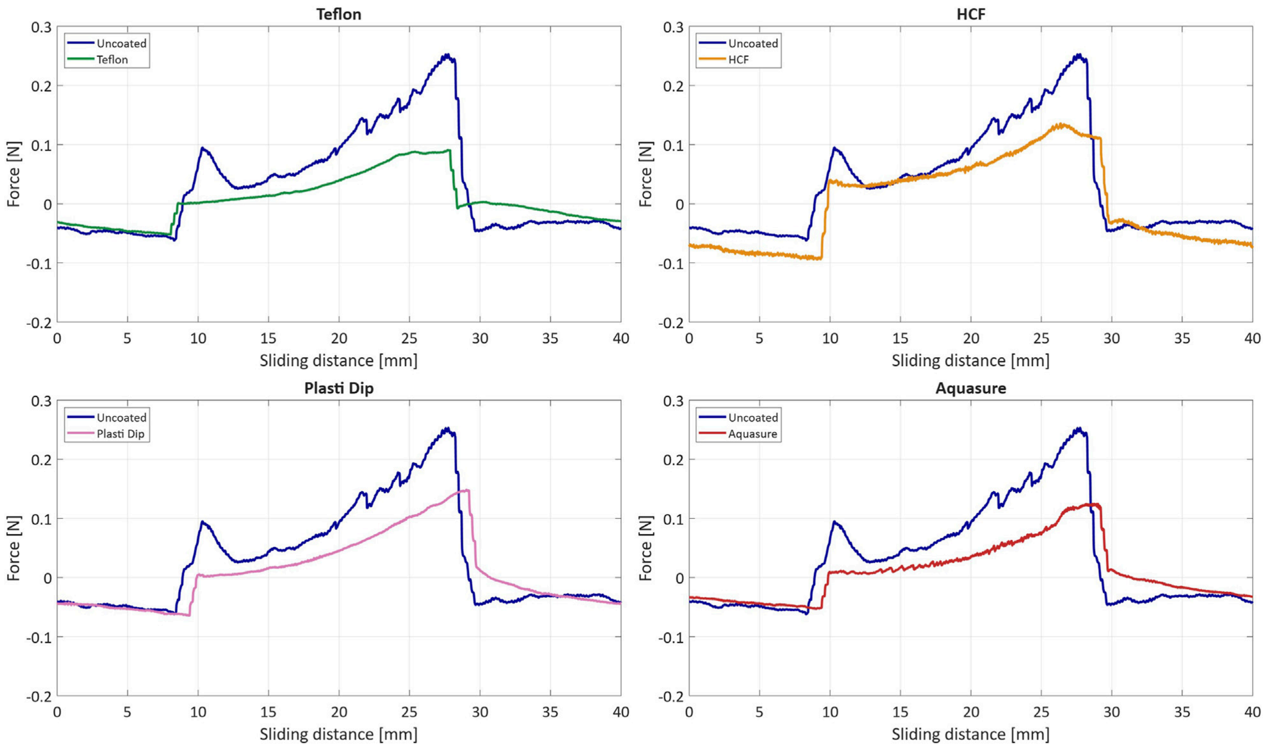

FIGURE 5
Mean force–displacement curves of selected coatings (Teflon spray, HCF, Plasti Dip, and Aquasure) in the BMF baby shampoo. Each curve represents the average of three representative measurement cycles.

TABLE 4 **Median catheter advancement forces of the first and last evaluated cycles and the resulting force change from the 60-cycle short-term stability experiment of the investigated coatings in baby shampoo.**

Coating	First cycle [N]	Last cycle [N]	Force change [N]
Plasti dip	0.04	0.05	0.01
RT 601	0.03	0.05	0.02
HCF	0.06	0.07	0.01
Aquasure	0.03	0.04	0.01
Silicone oil	0.06	0.08	0.02
Teflon spray	0.02	0.05	0.03
X-tec	0.05	0.07	0.02

uniform. In addition, a reduction in feed forces compared to the uncoated reference sample is observed, but more pronounced peaks occur. Moreover, in certain instances, the forces exerted during the return stroke can exceed those of other coatings.

The global median forces reported in Table 3 were calculated over the complete measurement series and therefore represent the overall tribological performance of each coating. In contrast, Table 4 illustrates the evolution of the median force from the first to the final measurement cycle in order to assess the short-term stability of the individual coating systems. Consequently, coatings exhibiting increasing friction during cyclic loading, such as Teflon spray, may show lower median forces during the initial cycles than their corresponding global median values reported in Table 3. The short-term stability of the coatings was evaluated in a separate measurement series consisting of 60 consecutive catheter advancement cycles in baby shampoo. To avoid an incomplete final cycle, the first 59 valid cycles were included in the evaluation. The results of the study are summarised in Table 4.

The most negligible alterations in median force were detected for Plasti Dip, HCF, and Aquasure. For these coatings, the force increased by a mere 0.01 N over the course of the test. RT 601, X-tec, and silicone oil demonstrated a increase of 0.02 N each. The most notable change was observed in the Teflon spray sample, which exhibited an increase in median force of 0.03 N between the initial and final cycles.

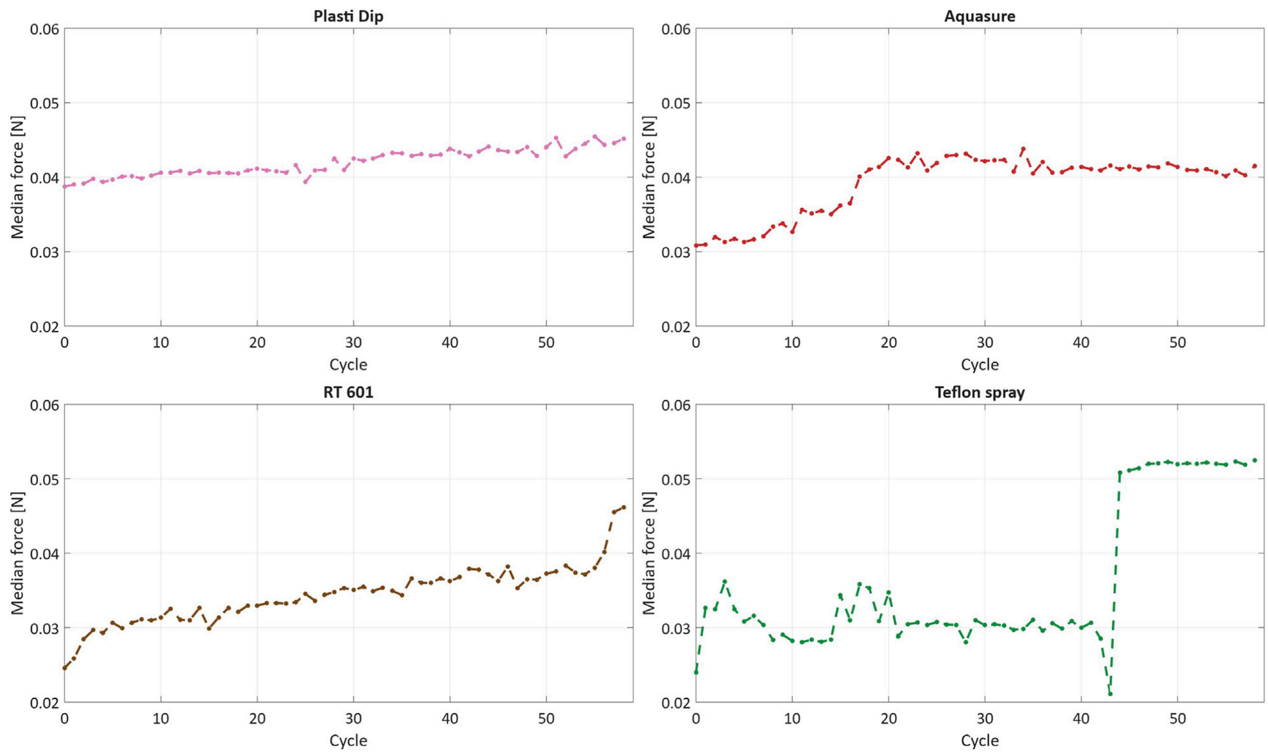

FIGURE 6
Development of median force over 59 cycles for selected coatings in baby shampoo.

The trend of the median force over the number of cycles for selected coatings is illustrated by Figure 6.

While Plasti Dip demonstrates a predominantly constant force trend throughout the entirety of the test, Aquasure and RT 601 exhibit a slight increase in the initial cycles, subsequently reaching a plateau. Initially, Teflon spray shows a low median force level, which only increases considerably after approximately 40 cycles. In conclusion, Plasti Dip, HCF and Aquasure demonstrated the least alteration in friction properties during the designated test period.

3.3 Coating handling and costs

In addition to tribological performance parameters, material cost and ease of application are also of central importance for practical use. With regard to application, the coating systems can be classified into three categories: easily applicable spray systems (Teflon spray, silicone oil) with very short application times but limited control over coating thickness; moderately complex systems such as Plasti Dip, HCF, and X-tec, which require surface pretreatment as well as defined drying and curing times; and complex systems such as Wacker RT 601 and Aquasure, which require additional process steps such as hot-air curing, the addition of accelerators, or active flushing of the lumen during the initial curing phase. The costs presented in Table 5 were normalized to 100 mL to improve comparability and primarily serve to provide a general overview of the costs of the investigated coating systems. It should be noted that silicone oil and Teflon spray are only partially comparable to the other coatings, as they are applied as sprays and the actual applied material quantity as well as real consumption are difficult to quantify. The cost comparison shows a range from approximately 2.5 € for diluted Plasti Dip to 23.0 € for the AquaSure mixture. Spray applications such as silicone oil and Teflon spray are considered cost-effective in practice despite comparable list prices, due to their lower material consumption. Additionally, it should be noted that HCF is exclusively sourced from the United Kingdom, which may result in additional shipping and potentially customs costs.

TABLE 5 Comparison of the normalized costs of the coating systems.

Coating	Batch size	Batch cost	Cost 100 mL
Plasti dip + Thinner (3:1)	1000 ml 1000 mL	~25 € ~11 €	2.5 €
RT 601	1000 ml	~124 €	12.4 €
HCF	750 mL	~33 €	4.4 €
Aquasure + Curing agent (3:1)	250 mL 30 mL	~35 € ~15 €	23.0 €
Silicone oil	400 mL	~10 €	2.5 €
Teflon spray	400 mL	~10 €	2.5 €
X-tec	1000 ml	~50 €	5.0 €

TABLE 6 Mean lumen diameter, standard deviation (SD), and diameter range determined by μCT.

Coating	Mean diameter [mm]	SD [mm]	Range [mm]
Uncoated	1.720	0.026	1.674–1.779
Plasti dip	1.623	0.037	1.544–1.695
RT 601	1.436	0.095	1.106–1.608
HCF	1.586	0.036	1.438–1.668
Aquasure	1.519	0.035	1.447–1.596
Teflon spray	1.632	0.011	1.609–1.662
X-tec	1.691	0.012	1.652–1.735

3.4 Micro-computed tomography

The coating systems examined as part of the force measurements provide an understanding of the tribological behavior of the materials, but do not allow for the determination of their geometric influence on the vessel model. Consequently, the coated samples were examined using μCT, and the resulting changes in the lumen were quantitatively evaluated. Given that silicone oil does not form a permanent coating due to its short-term tribological effect, this system was not analyzed using μCT. In order to investigate the reproducibility of the additive manufacturing process, three independently produced uncoated reference samples were examined (n = 3). The geometric parameters that were determined for all samples examined are summarized in Table 6.

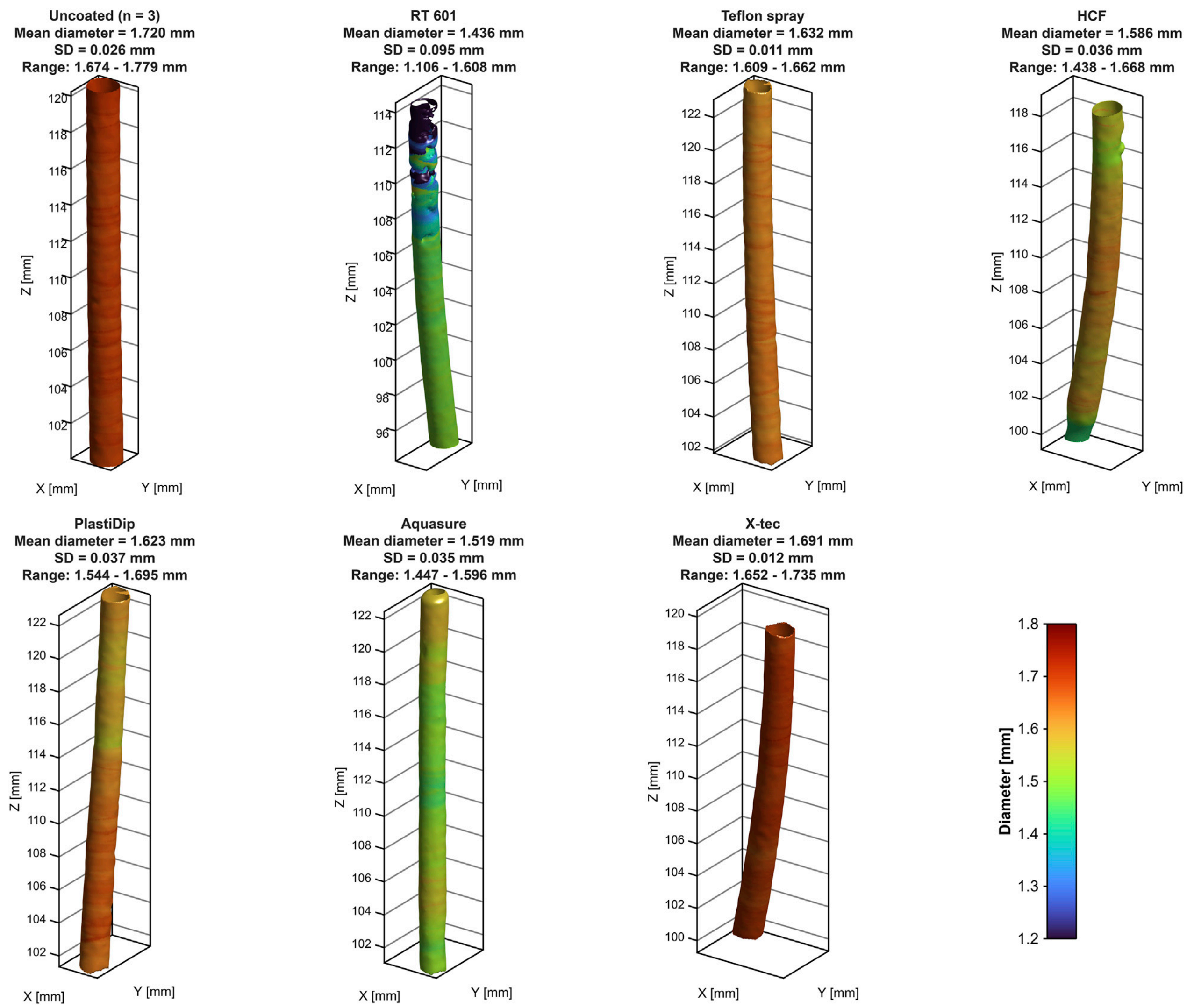

FIGURE 7
μCT-based heatmaps showing the spatial distribution of the lumen diameter for the investigated coating systems.

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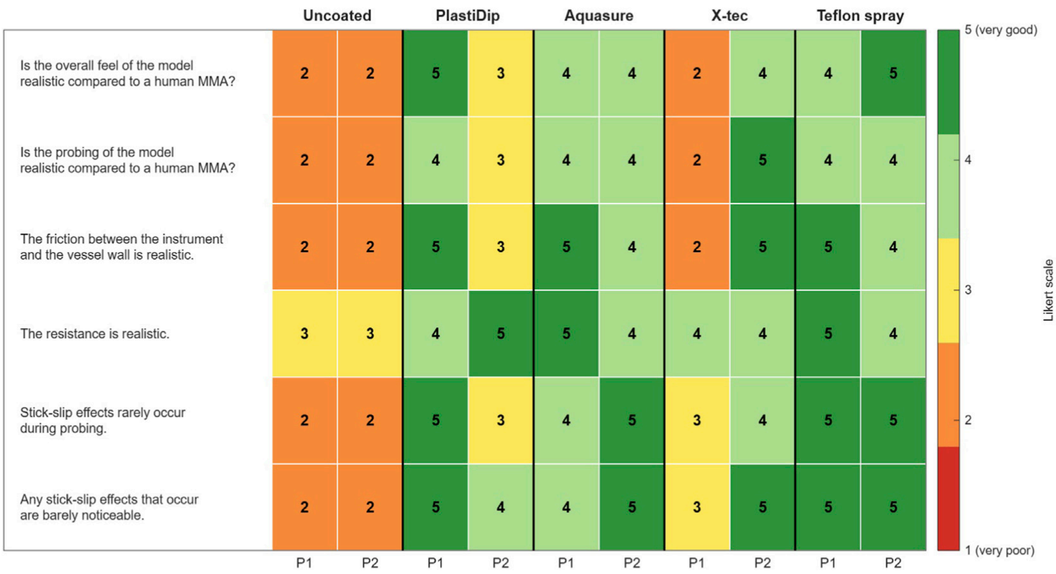

FIGURE 8
Evaluation results for each question and surface coating, based on the five-point Likert scale, presented using a heatmap.

Figure 7 presents the spatial diameter distributions as heat maps on the reconstructed STL models. For the uncoated reference, one of the three specimens is shown as an example, while the mean and standard deviation were calculated from all three reference specimens. The three uncoated samples exhibited only a slight deviation in their mean inner diameter, thereby confirming the high reproducibility of the PolyJet printing process and the µCT-based evaluation method. Concurrently, the heat map of the representative reference sample illustrates an inner diameter that exhibits minimal variation over the entire sample length, with no discernible local irregularities.

The investigation revealed that all of the coating systems examined resulted in a reduction in the free lumen cross-sectional area compared to the uncoated reference. However, the systems differed in terms of their geometric influence and the homogeneity of the applied layer. X-tec demonstrates the largest mean inner diameter and thus the smallest reduction in the free lumen. Concurrently, the heat map reveals a predominantly homogeneous diameter distribution, exhibiting only minor fluctuations. Teflon spray has been demonstrated to achieve the lowest standard deviation and exhibits a very uniform coating without pronounced local material accumulations. Conversely, RT 601 exhibited the most marked decrease in inner diameter and the most pronounced spatial inhomogeneity. The application of the heat map reveals considerable local material accumulations in the upper section of the sample. These accumulations are characterized by the highest standard deviation and the widest diameter range among all the coating systems examined.

The µCT analysis reveals substantial disparities in the coating behaviour of the systems examined. While Teflon spray and X-tec exhibit very homogeneous film formation with only a minor geometric impact on the lumen, HCF and, in particular, RT 601 result in a more pronounced reduction in the inner diameter and increased spatial inhomogeneity.

3.5 Application test

Based on the combined results of coating homogeneity, friction reduction, short-term stability, geometric preservation of the vascular lumen, as well as handling during coating application, Plasti Dip, Aquasure, X-tec, and Teflon spray were selected for subsequent clinical validation. Practical aspects such as material cost were considered only as secondary criteria where coatings showed comparable technical performance. The objective of this study was to investigate the extent to which the tribological properties determined in the mechanical tests were also subjectively perceived by experienced users. For the purpose of clinical validation, the coated vascular models were evaluated by two physicians specialising in interventional neuroradiology. These physicians employed a standardised questionnaire to assess the tactile feel, probeability, friction properties, and suitability for treatment training with HANNES. Figure 8 summarizes the participants' questionnaire responses using a heatmap based on a five-point Likert scale.

Both physicians noted that the uncoated model was only partially suitable for HANNES treatment training. In their comments, both physicians noted increased vascular resistance. Both physicians rated the categories *overall feel, realistic probing,* and *realistic friction* 2 out of 5 points. The realism of the resistance was rated with three points. Additionally, both evaluators rated the frequency and clarity of the stick-slip effects as high. Overall, the evaluations of Plasti Dip show a moderate degree of agreement between the two physicians. One physician rated the coating as suitable for training on treatment, while the other rated it as only partially suitable. The categories *overall feel, realistic probing*, and *realistic friction* received predominantly 3- to 5-point ratings. Stick-slip effects were described as ranging from barely present to mildly pronounced. Comments also noted a closed distal vascular and two non-contrastable, non-probed vascular. Both physicians unanimously rated Aquasure as suitable for treatment training.

Ratings for the categories *overall feel, realistic probing, realistic friction,* and *realistic resistance* were predominantly between four and five points. Both physicians rarely noted stick-slip effects. The coating was described as a good choice for training purposes and as providing a good balance between probeability and resistance. The X-tec coating produced the greatest discrepancy in ratings between the two evaluators. While one physician rated it as only partially suitable for treatment training, the other rated it as suitable. Accordingly, the categories *overall feel, realistic probing,* and *realistic friction* were rated differently. One physician described high and unrealistic resistance in the proximal model area in the comments, while the other physician rated the haptic feel as realistic despite the increased resistance. Both evaluators agreed that the Teflon spray coating was suitable for training purposes. The categories *overall feel, realistic probing, realistic friction*, and *realistic resistance* received consistently high ratings of between four and five points. Both physicians described stick-slip effects as rarely or barely noticeable. The coating was described as very pleasant to probe, and its suitability for training courses was emphasized in their comments.

4 Discussion

The present study investigated various coating systems with a view to optimising additively manufactured PolyJet small vascular models in terms of their tribological properties and their suitability for interventional training applications. Previous studies have demonstrated that PolyJet technology is particularly suitable for reproducing small-diameter vascular geometries with high dimensional accuracy, whereas its relatively high surface friction remains a major limitation for realistic endovascular simulation. Therefore, the objective of the present study was not to compare different manufacturing technologies but to improve the tribological performance of PolyJet-printed vascular models by evaluating different coating strategies. The primary outcome of the present study was the overall catheter advancement force of the complete experimental system, which included the vascular model, coating, BMF, catheter, and guidewire. The objective was not to distinguish the contributions of fluid drag and wall friction, but rather to compare the overall catheter advancement forces generated by different coating systems under standardized conditions. Among the investigated BMF, baby shampoo was selected for the subsequent coating investigations because it consistently combined low catheter advancement forces with a clear differentiation between the investigated coating systems. The objective of this selection was not to identify the BMF that most closely reproduces the tribological properties of native blood, but to establish standardized experimental conditions that enable a sensitive comparison of coating performance. Since quantitative reference values for catheter advancement forces in human cerebral vessels are currently unavailable, no objective target force could be defined. Furthermore, previous studies used substantially different experimental setups, such as simplified vascular geometries, pulling tests, and non-physiological boundary conditions, precluding a direct comparison of catheter advancement forces. Therefore, the perfusion medium was selected to reduce the excessive catheter advancement forces of the PolyJet models and to enable a reproducible comparison of the investigated coating systems, rather than to reproduce the exact tribological properties of native blood vessels. The suitability of the selected medium for interventional training was subsequently complemented by the clinical evaluation performed by experienced interventional neuroradiologists. The combination of roughness measurements, force measurements, μCT analyses, and clinical validation enabled a comprehensive evaluation of the coatings. This evaluation took into account not only friction reduction but also the geometric influence on the vascular model and the subjective perception of experienced users. The results of the roughness measurements demonstrated that a number of coating systems led to a substantial reduction in the surface roughness of the PolyJet models. Aquasure, Plasti Dip, and RT601, in particular, achieved the greatest improvements compared to the uncoated reference. While the preliminary roughness measurements indicated that several coatings reduced the outer surface roughness, it should be noted that these measurements served only as an initial screening of coating-induced surface modifications. Consequently, the force measurements provide the primary basis for evaluating the tribological performance of the investigated coating systems. Whilst coatings with low roughness have been shown to generally exhibit reduced feed forces, considerable differences have been observed among the individual systems in terms of force response and short-term stability. This suggests that, in addition to surface roughness, factors such as coating homogeneity, surface chemistry, and the ability of the coating to maintain a stable lubricating film during repeated catheter advancement contribute to the overall friction behaviour and should therefore be considered collectively when selecting suitable coating systems. This relationship was particularly evident in the force-time and force-displacement analyses. While Teflon spray, Plasti Dip, and Aquasure all produced low feed forces, they differed in terms of the uniformity of the force curve. Teflon spray and Plasti Dip demonstrated predominantly uniform force profiles, exhibiting only a few pronounced force peaks, whereas Aquasure, despite comparable low catheter advancement force, exhibited locally greater fluctuations. These local force fluctuations may contribute to transient irregularities during catheter advancement that can be perceived by the user despite a low overall median catheter advancement force. Furthermore, Teflon spray exhibited a distinct increase in catheter advancement force after approximately 40 loading cycles. As this increase occurred rather abruptly instead of progressively, it is more likely to reflect localized coating degradation or partial coating loss than continuous wear of the coating. However, the underlying mechanism was not investigated in the present study and should therefore be addressed in future work. The findings indicate that the median of the catheter advancement forces should not be the exclusive criterion for assessing tribological properties. Conversely, an analysis of the entire force curve yields supplementary information that is not discernible when considering only the mean catheter advancement force. This approach provides additional information on local force irregularities that is not captured by the median catheter advancement force alone. The μCT examinations provided supplementary insights into the tribological findings, elucidating the geometric influence of the individual coatings. While Teflon spray and X-tec exhibited very homogeneous coating formation with only a slight reduction in lumen diameter, RT601 showed the most pronounced localized material buildup and lumen narrowing, followed by HCF to a lesser extent. The observed local material accumulations can be attributed to the material properties and the comparatively complex application process. The findings indicate that low catheter advancement force alone is inadequate for the evaluation of a coating. The presence of uneven coating formation has the potential to result in localized increases in resistance, despite a concomitant reduction in roughness. Concurrently, this phenomenon can compromise the anatomical accuracy of the vascular model. This underscores the necessity of evaluating a coating not solely on the basis of tribological parameters but also in conjunction with its geometric impact on the vascular model. For interventional training models, therefore, a coating that is as homogeneous as possible is just as crucial as pure friction reduction. These findings were also reflected in the clinical validation. Overall, there was a high degree of concordance between the objective force measurements and the subjective assessment by the two interventional neuroradiologists. The Teflon spray and Aquasure coatings, which combined low advancement forces with predominantly uniform force curves, were unanimously rated by both users as suitable for training purposes. Concomitantly, only minor stick-slip effects were reported by the evaluators. Conversely, the uncoated PolyJet model was evaluated as only marginally suitable due to its elevated vascular resistance and notable friction. Both physicians described an increase in resistance as well as clearly perceptible stick-slip effects, which is consistent with the measured high catheter advancement forces and pronounced force peaks. In the case of Plasti Dip, it was demonstrated that low catheter advancement force alone does not guarantee an unreservedly positive clinical evaluation. Despite its excellent tribological properties, the presence of locally occluded distal vascular segments resulted in a lower subjective evaluation. The results of the study indicate that the subjective perception of frictional force is not solely determined by the absolute magnitude of the force. Instead, the combination of low catheter advancement force, a smooth force curve without pronounced force peaks, and a homogeneous coating without local narrowings of the vessel lumen appears to be decisive for a realistic haptic impression. In addition to functional properties, economic and practical considerations also play an important role in subsequent applications. Teflon spray and silicone oil can be applied in a matter of seconds without any pretreatment, and due to their low material consumption, result in low application costs. However, they allow only limited control over the coating thickness. Conversely, Aquasure and RT601 necessitate considerably more intricate application procedures, encompassing supplementary steps and protracted curing periods. Plasti Dip offers a satisfactory compromise in terms of effort and cost, but requires optimization of the coating process to reliably prevent localized material buildup. The findings demonstrate that the selection of an appropriate coating invariably necessitates a compromise among tribological performance, geometric accuracy, processing effort, and cost. A comparison of the requirements defined at the study's inception with the subsequent outcomes reveals the attainment of key development goals. A multitude of coating systems have been demonstrated to effectively mitigate surface roughness and reduce catheter advancement forces. Concurrently, Teflon spray and X-tec, in particular, exhibited predominantly homogeneous coating formation, exhibiting only a marginal effect on the lumen diameter. In regard to a straightforward, cost-effective application that can be seamlessly integrated into existing manufacturing processes, spray coatings in particular have demonstrated their merits. However, a systematic investigation of the long-term durability and aging behavior of the coating systems was beyond the scope of this study. The abrupt increase in catheter advancement force observed for the Teflon spray coating after approximately 40 loading cycles highlights the need for future studies to address coating degradation mechanisms and long-term durability under repeated use.

5 Limitations

The validity of the study is constrained by several factors. Initially, roughness measurements were taken on the coated outer surface of the specimen and were used only for a preliminary screening of coating-induced surface modifications. Consequently, they cannot directly represent the tribologically relevant inner lumen surface, where catheter advancement takes place. Second, all coating systems were evaluated under identical experimental conditions using a single, constant catheter advancement speed. The objective of the present study was to compare the relative performance of different coating systems under standardized conditions rather than to investigate the influence of catheter advancement velocity on the measured forces. Future studies should therefore evaluate the effect of different advancement speeds on the performance of selected coating systems. Due to the limited availability of the instruments tribological analyses were performed on only one sample per coating (n = 1). While the concluding repeat measurement of the uncoated reference sample demonstrated stable performance of the experimental setup throughout the experiments and indicate no relevant influence of potential wear effects, it is not feasible to infer conclusions regarding the statistical variability of the individual coating systems. Consequently, the results of this study should be interpreted as an exploratory investigation and subsequently validated in future studies with augmented sample sizes. A systematic investigation of the long-term durability and ageing behaviour of the coatings under repeated mechanical loading was not conducted. Furthermore, the clinical validation was performed by only two experienced interventional neuroradiologists. The findings thus permit preliminary conclusions regarding the clinical relevance of the objectively measured parameters. However, these conclusions must be substantiated in larger studies with a greater number of investigators. Furthermore, the physicians evaluated the complete HANNES simulator rather than the coated MMA model in isolation. Consequently, the clinical assessment reflects the overall performance of the integrated training system, including the interaction between the vascular model, coating, BMF, and simulation environment. While this holistic evaluation closely represents the intended clinical training scenario, it does not allow the subjective ratings to be attributed exclusively to the investigated coating systems.

6 Conclusion

In summary, the present study demonstrates that surface roughness alone is insufficient to assess the performance of coated PolyJet-printed vascular models. Instead, the primary determining factor is the overall performance depends on the combination of homogeneous layer formation, low catheter advancement forces, uniform force distribution, and reproducible application. No single coating system proved superior in every evaluated category. Teflon spray demonstrated its efficacy through its simple and cost-effective application, homogeneous coating formation, and a high degree of agreement between objective measurements and clinical evaluation. However, the observed increase in catheter advancement force after approximately 40 loading cycles indicates that its long-term durability under repeated use requires further investigation. Aquasure demonstrated the lowest catheter advancement forces and received consistently positive ratings from physicians, although it necessitates a substantially greater effort to apply. Plasti Dip demonstrated positive overall handling characteristics and clinical ratings. However, further optimization of the coating application process is necessary. Therefore, when selecting a coating system, consider the intended application and the relative importance of friction reduction, coating homogeneity, ease of application, durability, cost, and clinical perception. Consequently, subsequent studies should examine the transferability of the coating systems to other additively manufactured materials. Moreover, these studies should assess the long-term stability of the coatings under repeated mechanical stress. This could result in the formulation of recommendations concerning requisite recoating intervals in practical training settings. In particular, future studies should investigate the mechanism underlying the abrupt increase in catheter advancement force observed for the Teflon spray coating after approximately 40 loading cycles and determine whether this behaviour is associated with localized coating degradation. In addition, the optimization of the Plasti Dip application process appears to be a rational approach. Given the material's recent availability as a spray coating, further investigation is warranted to ascertain its potential to enhance homogeneous layer formation and mitigate the localized vessel occlusions observed in this study. Finally, clinical validation should be conducted in a larger multicenter study with a greater number of interventional users to further substantiate the relationship between objective tribological parameters and subjective perception.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ES: Writing – original draft, Writing – review and editing, Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization. JS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. MB: Validation, Writing – review and editing. FF: Validation, Writing – review and editing. MW: Validation, Writing – review and editing. JF: Validation, Writing – review and editing. DK: Project administration, Resources, Supervision, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI was used to improve the language and readability of the manuscript. All scientific content, data analysis, interpretation, and final manuscript revisions were performed and verified by the authors.

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