

Aerodynamic Effects of Localized Textured Calf Tapes in Triathlon: A Wind Tunnel Screening Investigation

Arnaud Ménétrier¹

arnaud.menetrier@laposte.net

Université Marie et Louis Pasteur

Maxence Ramage¹

Université Marie et Louis Pasteur

Rémy Cavecchia²

AerOptimum

Research Article

Keywords: Triathlon, Aerodynamics, Cycling, Wind tunnel, Surface roughness, Sports engineering

Posted Date: October 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11268351/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: Competing interest reported. Arnaud Ménétrier is employed by Compressport. The company had no role in the study design, data collection, data analysis, interpretation of the results or preparation of the manuscript.

Abstract

Cycling is the fastest discipline of long-distance triathlon, where aerodynamic drag represents the main resistive force opposing forward motion. Consequently, even small reductions in drag may translate into meaningful performance gains. This preliminary engineering investigation evaluated the aerodynamic potential of a localized textured calf tape concept and identified promising surface configurations for subsequent athlete-based validation.

Wind tunnel testing was performed using a standardized rigid leg model to maximize measurement repeatability during early-stage product development. Six textured tape configurations, combining three dot widths (7, 15 and 30 mm) with two thicknesses (1 and 2 mm), were compared with an untreated control and a commercially available aerodynamic calf sleeve. Testing was conducted at air velocities of 40 and 45 km·h⁻¹ and yaw angles of 0°, 5°, 10° and 15°. Aerodynamic performance was assessed from measured drag force, estimated aerodynamic drag area, and aerodynamic power requirement. Measurement repeatability was high, with a mean coefficient of variation of 0.36%.

All textured tape configurations reduced aerodynamic drag relative to the control, although the magnitude of the reduction depended on dot geometry, air velocity, and yaw angle. The 15 × 2 mm configuration demonstrated the best overall performance, producing up to an 11% reduction in estimated aerodynamic drag area and a 5.1 W reduction in aerodynamic power requirement at 45 km·h⁻¹ and 15° yaw, compared with 6.2 W for the reference calf sleeve.

These findings identify promising localized surface architectures for further validation using full-body mannequins, athlete-based wind tunnel testing, and field studies.

1. Introduction

In cycling and long-distance triathlon, aerodynamic drag is the predominant resistive force opposing forward motion at racing speeds, accounting for approximately 80–90% of the total mechanical power required on flat terrain (1–3). Consequently, even relatively small reductions in aerodynamic drag may translate into meaningful improvements in cycling performance, particularly during prolonged individual time-trials and long-distance triathlon events (1,2).

Over the past two decades, aerodynamic optimization has become a major area of innovation in endurance sports. Beyond bicycle design and rider positioning, increasing attention has been devoted to technical sports garments and engineered textile surfaces capable of modifying airflow around the athlete (4–7). Previous studies have demonstrated that carefully designed surface textures can alter boundary-layer behaviour, delay flow separation, and reduce aerodynamic drag, leading to measurable performance improvements under specific conditions (4,5,8).

Among the different body segments, the calf appears particularly relevant from an aerodynamic perspective. Its geometry resembles that of a bluff cylindrical body, for which controlled surface

roughness is known to influence boundary-layer transition, flow separation, and pressure drag (8,9). This aerodynamic rationale has driven the development of commercially available calf sleeves and socks specifically designed to improve aerodynamic performance during cycling and triathlon competition (4,5).

Although aerodynamic calf sleeves may provide measurable drag reductions, their practical use in triathlon remains subject to several limitations. Under hot environmental conditions, these garments may impair thermal comfort and reduce heat dissipation (10). Furthermore, according to World Triathlon and Ironman regulations, garments covering the calf may not be permitted during the swim segment when water temperatures exceed specific thresholds. Athletes may therefore be required to put on aerodynamic calf sleeves during the swim-to-bike transition, increasing transition time and potentially offsetting part of the aerodynamic benefit obtained during the cycling segment.

Interest in localized calf surface texturing increased following the INEOS 1:59 Challenge, during which marathon runner Eliud Kipchoge wore visible textured strips on his calves. Although the exact function of these devices has never been publicly disclosed, they stimulated discussion regarding the possibility that localized surface modifications could influence airflow around the lower leg. Together with recent advances in aerodynamic textile technologies, these observations inspired the development of alternative surface-texturing strategies specifically adapted to the practical constraints of triathlon.

Accordingly, a novel textured adhesive tape concept was developed for triathlon. Instead of covering the entire calf with a compressive garment, this approach aims to introduce localized surface roughness using lightweight textured adhesive strips applied directly to the skin. Such a strategy could preserve much of the aerodynamic benefit associated with surface texturing while reducing material coverage, minimizing thermal burden and simplifying race logistics.

Within engineering product development, simplified experimental models are routinely used during the early stages of development to compare multiple design concepts under highly repeatable conditions before progressing toward more representative evaluations. The present study therefore employed a standardized rigid leg model to identify the most promising textured tape configurations before athlete-based validation.

The objective of this preliminary investigation was to evaluate the aerodynamic potential of localized textured adhesive tapes applied to the calf and to determine which surface geometries provided the greatest aerodynamic benefit under controlled wind tunnel conditions. It was hypothesized that localized surface texturing would reduce aerodynamic drag and the associated aerodynamic power requirement relative to the untreated control configuration.

2. Methods

2.1 Experimental Design

The present study was designed as an engineering-based screening investigation aimed at comparing several textured tape architectures under highly controlled laboratory conditions. Rather than reproducing the complete aerodynamic behaviour of a cyclist, the objective was to identify the most promising surface-texture configurations before validation using more representative experimental models.

Accordingly, a standardized rigid leg model was selected to provide a highly repeatable experimental platform, allowing direct comparison of multiple surface-texture configurations while minimizing experimental variability associated with human testing.

2.2 Wind Tunnel Facility

Aerodynamic testing was conducted at the AerOptimum closed-circuit Prandtl-type wind tunnel (Magny-Cours, France). The test section measured 2.30×2.05 m and provided highly controlled airflow conditions suitable for aerodynamic product development and experimental comparison.

Environmental conditions, including air temperature, atmospheric pressure, and air density, were continuously monitored throughout testing to ensure measurement consistency. Airflow velocity was continuously monitored and maintained at the prescribed test speeds throughout each experimental session.

2.3 Experimental Model

A standardized rigid leg model was used throughout the study (Fig. 1). The use of this model substantially reduced variability associated with human positioning, involuntary movements, soft tissue deformation, muscle contractions, and pedalling kinematics, thereby allowing highly reproducible comparisons between tape configurations.

The purpose of using an isolated leg model was not to reproduce the complete aerodynamic behaviour of a cyclist but to provide a simplified and highly repeatable experimental platform suitable for early-stage product development and concept screening.

2.4 Experimental Protocol

Testing was performed at airflow velocities of 40 and 45 km·h⁻¹, corresponding to typical cycling speeds encountered during competitive middle- and long-distance triathlon events (2,11).

Yaw angles of 0°, 5°, 10°, and 15° were reproduced by rotating the leg model relative to the incoming airflow in order to simulate realistic crosswind conditions commonly experienced during outdoor cycling (2,11).

The orientation of the leg model remained unchanged throughout the entire testing session.

Aerodynamic drag force (F_x) was measured using a high-sensitivity strain gauge-based force platform integrated into the wind tunnel structure.

For each condition, drag force, air temperature, atmospheric pressure, and dynamic pressure were recorded continuously over a 30-second acquisition period at a sampling frequency of 100 Hz. Mean values were subsequently calculated for all variables.

2.5 Development of the Textured Tapes

The textured adhesive tapes were specifically developed for triathlon applications. The tape concept was inspired by localized surface texturing observed during the INEOS 1:59 Challenge together with existing aerodynamic textile technologies currently used in cycling and triathlon. The devices consisted of lightweight textured adhesive strips designed to introduce controlled surface roughness directly onto the calf.

Six tape configurations were evaluated by combining three dot widths (7, 15 and 30 mm) with two dot thicknesses (1 and 2 mm) (Fig. 2).

These geometries were selected to cover a broad range of controlled surface roughness characteristics while remaining compatible with practical manufacturing constraints.

The tapes were positioned symmetrically on both sides of the leg model (Fig. 3) in order to avoid introducing asymmetrical airflow disturbances.

A commercially available aerodynamic calf sleeve was included as a reference condition (Fig. 4), together with a control condition consisting of the rigid leg model without textured tapes (Fig. 1).

2.6 Aerodynamic Calculations

The primary measured outcome was aerodynamic drag force (F_x).

Aerodynamic drag area (C_dA) was subsequently estimated using the standard aerodynamic relationship:

$$CdA = \frac{2F}{\rho V^2}$$

Where F = measured drag force; ρ = air density; V = airflow velocity.

Estimated aerodynamic power requirement was then calculated as:

$$P = \frac{1}{2} \rho C_d A V^3$$

Where P represents the aerodynamic power required to overcome drag.

These calculations enabled direct comparison of the aerodynamic performance of each configuration independently of air density and test velocity.

2.7 Measurement Repeatability

Measurement repeatability was assessed through repeated trials performed under identical experimental conditions.

The mean coefficient of variation (CV) of drag force measurements was 0.36%, demonstrating excellent repeatability and confirming that the experimental setup was sufficiently sensitive to resolve the relatively small aerodynamic differences observed between configurations.

3. Results

3.1 Aerodynamic Drag Force

Measured aerodynamic drag force increased progressively with both airflow velocity and yaw angle across all experimental conditions (Table 1). Relative to the control configuration (rigid leg model without textured tapes), the commercially available aerodynamic calf sleeve and all textured tape configurations reduced measured drag force under at least some experimental conditions. However, the magnitude of the reduction depended on tape geometry, airflow velocity, and yaw angle. Across virtually all experimental conditions, textured tapes incorporating 2 mm-thick dots consistently outperformed their corresponding 1 mm-thick configurations. Likewise, configurations incorporating 30 mm dots generally produced the smallest reductions in drag force. Among the textured tape concepts evaluated, the 7 mm × 2 mm and 15 mm × 2 mm configurations consistently demonstrated the lowest drag force values across the majority of testing conditions.

Table 1

Measured aerodynamic drag force (F_x , kg) across airflow velocities and yaw-angle conditions.

Aerodynamic drag (F_x in kg)								
Velocity (km.h ⁻¹)	40	40	40	40	45	45	45	45
Angle (°)	0	5	10	15	0	5	10	15
Plastic leg only	0,2818	0,3025	0,3252	0,3266	0,3636	0,3858	0,4102	0,4103
Sleeve	0,2686	0,2847	0,2964	0,2965	0,3387	0,3580	0,3762	0,3690
7 mm x 1 mm dots	0,2723	0,2888	0,3173	0,3172	0,3281	0,3534	0,3838	0,3968
7 mm x 2 mm dots	0,2613	0,2819	0,2997	0,3022	0,3278	0,3513	0,3746	0,3757
15 mm x 1 mm dots	0,2713	0,2912	0,3060	0,3121	0,3334	0,3587	0,3754	0,3899
15 mm x 2 mm dots	0,2612	0,2759	0,3001	0,3049	0,3262	0,3398	0,3735	0,3714
30 mm x 1 mm dots	0,2724	0,2959	0,3113	0,3221	0,3382	0,3608	0,3824	0,3917
30 mm x 2 mm dots	0,2736	0,2930	0,3107	0,3145	0,3374	0,3580	0,3809	0,3797

3.2 Estimated Aerodynamic Drag Area (CdA)

Estimated CdA closely reflected the trends observed for measured drag force (Table 2). Compared with the control configuration, all textured tape configurations reduced estimated CdA, although the magnitude of the reduction varied according to tape geometry and testing conditions. The largest reductions were consistently obtained with the 7 mm × 2 mm and 15 mm × 2 mm configurations. Under the most favourable testing conditions (45 km·h⁻¹), these configurations reduced estimated CdA by approximately 7–10% relative to the control configuration. Conversely, configurations incorporating 30 mm dots consistently produced smaller reductions in CdA than the corresponding 7 mm and 15 mm configurations.

Table 2

Estimated aerodynamic drag area (CdA, m²) across airflow velocities and yaw-angle conditions.

CdA (in m²)								
Velocity (km.h ⁻¹)	40	40	40	40	45	45	45	45
Angle (°)	0	5	10	15	0	5	10	15
Plastic leg only	0,0373	0,0403	0,0443	0,0464	0,0380	0,0406	0,0444	0,0461
Sleeve	0,0351	0,0375	0,0399	0,0416	0,0351	0,0374	0,0403	0,0410
7 mm x 1 mm dots	0,0360	0,0385	0,0432	0,0450	0,0346	0,0375	0,0419	0,0449
7 mm x 2 mm dots	0,0344	0,0374	0,0406	0,0425	0,0341	0,0369	0,0404	0,0421
15 mm x 1 mm dots	0,0360	0,0388	0,0418	0,0443	0,0352	0,0381	0,0409	0,0441
15 mm x 2 mm dots	0,0344	0,0366	0,0408	0,0429	0,0342	0,0361	0,0406	0,0420
30 mm x 1 mm dots	0,0363	0,0397	0,0427	0,0458	0,0359	0,0387	0,0420	0,0446
30 mm x 2 mm dots	0,0362	0,0389	0,0422	0,0446	0,0357	0,0382	0,0415	0,0432

3.3 Estimated Aerodynamic Power Requirement

Estimated aerodynamic power requirement increased with airflow velocity and yaw angle across all experimental conditions (Table 3; Fig. 5). Relative to the control configuration, all textured tape configurations reduced estimated aerodynamic power requirement, although the magnitude of the reduction varied according to tape geometry and testing conditions. The commercially available aerodynamic calf sleeve consistently produced the lowest estimated aerodynamic power requirement. Among the textured tape concepts, the 7 mm × 2 mm and 15 mm × 2 mm configurations consistently demonstrated the greatest reductions in estimated aerodynamic power across the majority of testing conditions. The greatest reduction among the textured tape configurations was observed for the 7 mm × 2 mm design at 45 km·h⁻¹ and 15° yaw angle, where the estimated aerodynamic power requirement decreased by 4.8 W relative to the control configuration. Under the same conditions, the aerodynamic calf sleeve reduced the estimated aerodynamic power requirement by 6.2 W.

Table 3

Estimated aerodynamic power requirement (W) across airflow velocities and yaw-angle conditions.

Estimated aerodynamic power (in W)								
Velocity (km.h ⁻¹)	40	40	40	40	45	45	45	45
Angle (°)	0	5	10	15	0	5	10	15
Plastic leg only	30,8624	33,3497	36,5336	38,4073	44,6811	47,7141	52,2555	54,3252
Sleeve	28,8779	30,7906	32,8357	34,1865	41,2191	43,8713	47,2814	48,1451
7 mm x 1 mm dots	29,6978	31,8139	35,5946	37,1387	40,7998	44,2945	49,4964	52,9877
7 mm x 2 mm dots	28,4127	30,8944	33,5176	35,0490	40,0201	43,4245	47,6346	49,5310
15 mm x 1 mm dots	29,7428	31,9608	34,5140	36,5347	41,5686	44,9138	48,3539	52,1391
15 mm x 2 mm dots	28,3122	30,1268	33,6070	35,2022	40,1714	42,5828	47,8555	49,6442
30 mm x 1 mm dots	30,0700	32,8036	35,3284	37,8758	42,4904	45,8079	49,7022	52,7166
30 mm x 2 mm dots	29,8487	32,0535	34,7386	36,7325	42,2392	45,1372	49,0380	51,0889

3.4 Overall Performance of the Tested Configurations

The relative ranking of the tested configurations remained remarkably consistent across airflow velocities and yaw-angle conditions (Table 4). Across virtually all experimental conditions, textured tapes incorporating 2 mm-thick dots systematically outperformed their corresponding 1 mm-thick configurations. Similarly, smaller dot diameters generally produced greater aerodynamic improvements than larger diameters. Overall, the 7 mm × 2 mm and 15 mm × 2 mm configurations consistently ranked among the best-performing textured tape concepts evaluated in the present study, whereas configurations incorporating 30 mm dots generally produced the smallest aerodynamic improvements.

Table 4
Summary of the aerodynamic performance of the tested configurations

Configuration	Maximum CdA reduction vs. control (%)	Maximum power saving vs. control (W)	Overall performance
Sleeve	11.0	6.2	★★★★
15 mm x 2 mm dots	11.1	5.1	★★★
7 mm x 2 mm dots	10.3	4.8	★★★
7 mm x 1 mm dots	9.0	3,9	★★
15 mm x 1 mm dots	7.7	3.9	★★
30 mm x 2 mm dots	7.8	2.5	★
30 mm x 1 mm dots	5.4	2.0	★

4. Discussion

4.1 Principal Findings

The present study investigated the aerodynamic effects of six textured adhesive tape configurations applied to the calf using a highly repeatable wind tunnel protocol based on a standardized rigid leg model. The principal finding was that all textured tape configurations reduced aerodynamic drag, estimated CdA and estimated aerodynamic power requirement relative to the untreated control condition. However, the magnitude of these improvements depended on tape geometry, airflow velocity and yaw angle.

Among the six configurations evaluated, the 7 mm × 2 mm and 15 mm × 2 mm designs consistently demonstrated the greatest aerodynamic benefits, whereas configurations incorporating 30 mm dots produced the smallest improvements. Increasing dot thickness from 1 mm to 2 mm also systematically enhanced aerodynamic performance across most testing conditions, highlighting the importance of surface geometry in determining aerodynamic effectiveness.

Aerodynamic benefits became progressively greater as airflow velocity and yaw angle increased. The largest estimated power saving achieved by the textured tape configurations reached 4.8 W at 45 km·h⁻¹ and 15° yaw, compared with 6.2 W for the reference aerodynamic calf sleeve tested under identical conditions. Although the calf sleeve remained the most effective configuration, the best-performing textured tape approached its aerodynamic performance while requiring substantially less material coverage.

Taken together, these findings demonstrate that localized modification of calf surface roughness can measurably influence aerodynamic performance within a simplified experimental model. More importantly, they identify surface geometry as a key design parameter, indicating that relatively small variations in roughness characteristics can substantially influence aerodynamic behaviour (12,13).

4.2 Influence of Surface Geometry

The aerodynamic performance of the textured tape configurations was strongly influenced by surface geometry. More specifically, 2 mm-thick dots consistently outperformed their corresponding 1 mm-thick configurations, whereas 30 mm dots generally produced smaller aerodynamic improvements than 7 mm and 15 mm dots.

These observations are consistent with the fundamental principles of bluff-body aerodynamics. For cylindrical and bluff-body geometries, surface roughness directly influences boundary-layer transition, flow separation and pressure drag (8,9,14,15). When appropriately dimensioned, roughness elements promote an earlier transition from laminar to turbulent flow, allowing the boundary layer to retain greater kinetic energy and remain attached to the surface for longer (8,14). Delayed flow separation subsequently reduces wake size and pressure drag, which represents the dominant component of aerodynamic resistance for bluff bodies (8,13).

Conversely, roughness that is either insufficient or excessive may reduce these aerodynamic benefits. Roughness elements that are too small may fail to trigger an effective boundary-layer transition, whereas excessively large elements may increase skin-friction drag or generate localized flow disturbances that offset potential reductions in pressure drag (8,13,16). Within the present experimental conditions, the best-performing configurations appeared to provide the most favourable balance between these competing aerodynamic mechanisms.

The present results further suggest that aerodynamic performance depends not only on the amount of material applied to the surface, but also on its geometric organization. Smaller yet thicker roughness elements appeared to modify local boundary-layer behaviour more effectively than larger surface features (12,13,16). Although the present experimental design does not permit direct visualization of the underlying flow mechanisms, this interpretation agrees with previous investigations on textured surfaces and engineered aerodynamic textiles, which have demonstrated that drag reduction depends strongly on the size, geometry and spatial distribution of roughness elements (4,5,13,16).

4.3 Influence of Airflow Velocity and Yaw Angle

Aerodynamic benefits increased progressively with both airflow velocity and yaw angle, with the largest reductions in drag, estimated CdA and aerodynamic power requirement consistently observed at 45 km·h⁻¹ under 10° and 15° yaw angles.

This behaviour is consistent with the fundamental principles of external aerodynamics. Aerodynamic drag increases approximately with the square of airflow velocity, whereas the power required to

overcome drag increases approximately with its cube (1,17). Consequently, relatively small reductions in drag become progressively more valuable as cycling speed increases, resulting in larger absolute power savings.

The greater aerodynamic benefit observed at 15° yaw angles is also consistent with previous studies investigating aerodynamic garments and textured surfaces in cycling (18). Under crosswind conditions, the airflow interacts with the lower leg at a greater effective angle, modifying flow separation and wake development. Localized surface roughness may therefore exert a stronger influence on boundary-layer behaviour than under purely frontal airflow (18).

The present findings further suggest that the aerodynamic effectiveness of textured tapes depends on the combined interaction between airflow velocity and yaw angle rather than on either parameter alone. Although direct flow visualization was beyond the scope of the present study, one plausible explanation is that localized surface roughness promoted a more favourable boundary-layer development and delayed flow separation under high-speed, moderate-yaw conditions, thereby reducing wake size and pressure drag (8,14,18). Similar mechanisms have been reported for rough bluff bodies, engineered aerodynamic surfaces and textured sports textiles (4,5,16).

4.4 Practical implications

Beyond the aerodynamic findings, the present work highlights several potential practical advantages of localized surface texturing for triathlon. Unlike conventional aerodynamic calf sleeves, the proposed concept modifies airflow through selective surface texturing while minimizing material coverage.

This design strategy may offer benefits extending beyond aerodynamics. Because only a limited portion of the calf is covered, localized textured tapes could potentially reduce the thermal burden associated with full-coverage compression sleeves, particularly during competitions performed in hot environmental conditions (10). Although thermal responses were not evaluated in the present study, previous investigations have shown that garments covering large body areas can influence heat dissipation and thermal perception during prolonged endurance exercise.

Unlike conventional calf sleeves, localized textured tapes could also simplify race logistics by avoiding full calf coverage while approaching the aerodynamic performance of a conventional aerodynamic calf sleeve. However, this potential advantage remains to be confirmed through future investigations evaluating adhesion, durability, athlete comfort and regulatory compliance under representative competition conditions.

More broadly, the present work introduces an alternative engineering strategy for the development of aerodynamic sports apparel. Rather than maximizing textile coverage, future aerodynamic devices may be designed by strategically applying localized surface textures only where they provide the greatest aerodynamic benefit. If confirmed through athlete-based wind tunnel testing and field validation, such an approach could represent a promising new direction for aerodynamic optimization in triathlon and other endurance sports.

4.5 Limitations

The use of a standardized rigid leg model provided a highly repeatable experimental platform, substantially reducing variability associated with human positioning, soft tissue deformation and pedalling kinematics. This approach resulted in excellent measurement repeatability, with a mean coefficient of variation of only 0.36%, enabling reliable comparison of relatively small aerodynamic differences between configurations. The aerodynamic differences observed between the best-performing configurations consistently exceeded the measurement variability, supporting the robustness of the observed ranking under the present experimental conditions.

Several limitations should nevertheless be acknowledged. The isolated rigid leg model does not reproduce the complete aerodynamic behaviour of a cyclist, where interactions between the rider, bicycle and surrounding airflow contribute to overall aerodynamic performance. Likewise, the experimental setup does not account for pedalling motion, changes in joint angle or soft tissue deformation occurring during real cycling.

Future investigations should follow a progressive validation strategy, beginning with full-body mannequins and athlete-based wind tunnel testing before proceeding to real-world field studies. Such investigations should evaluate not only aerodynamic performance but also thermal responses, durability following swimming and athlete acceptance under representative competition conditions.

5. Conclusion

The present study evaluated the aerodynamic potential of localized textured adhesive tapes applied to the calf using a highly repeatable wind tunnel protocol based on a standardized rigid leg model. Within the limitations of this engineering-based screening investigation, all textured tape configurations reduced aerodynamic drag relative to the untreated control condition, although the magnitude of the improvement depended on dot geometry, airflow velocity and yaw angle.

Among the six configurations evaluated, the 7 mm × 2 mm and 15 mm × 2 mm designs consistently demonstrated the greatest aerodynamic benefits. These findings indicate that relatively small modifications in surface geometry can substantially influence aerodynamic performance, highlighting the importance of optimizing roughness characteristics rather than simply increasing surface coverage.

Beyond the specific concept investigated, the present work supports the feasibility of localized surface texturing as an alternative approach to conventional full-coverage aerodynamic garments. This strategy may provide a promising compromise between aerodynamic performance, material coverage and the practical constraints specific to triathlon.

Declarations

Competing Interests:

Arnaud Ménétrier is employed by Compressport. The company had no role in the study design, data collection, data analysis, interpretation of the results or preparation of the manuscript.

Acknowledgements

The authors would like to thank AerOptimum (Magny-Cours, France) for providing access to the wind tunnel facilities and technical support during testing.

Funding:

This research received no external funding.

Author Contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Arnaud Ménétrier, Maxence Ramage and Rémy Cavecchia. The first draft of the manuscript was written by Arnaud Ménétrier and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

References

1. Martin JC, Milliken DL, Cobb JE, McFadden KL, Coggan AR. Validation of a mathematical model for road cycling power. *J Appl Biomech*. 1998;14(3):276-291. doi:10.1123/jab.14.3.276
2. Barry N, Burton D, Sheridan J, Thompson M, Brown NAT. Aerodynamic performance and riding posture in road cycling and triathlon. *Proc Inst Mech Eng P J Sports Eng Technol*. 2015;229(1):28-38. doi:10.1177/1754337114549876
3. Debraux P, Grappe F, Manolova AV, Bertucci W. Aerodynamic drag in cycling: methods of assessment. *Sports Biomech*. 2011;10(3):197-218. doi:10.1080/14763141.2011.592209
4. Oggiano L, Brownlie L, Troynikov O, Bardal LM, Sæter C, Sætran L. A review on skin suits and sport garment aerodynamics: guidelines and state of the art. *Procedia Eng*. 2013;60:91-98. doi:10.1016/j.proeng.2013.07.018
5. Chowdhury H, Alam F, Subic A. Aerodynamic performance evaluation of sports textile. *Procedia Eng*. 2010;2(2):2517-2522. doi:10.1016/j.proeng.2010.04.025
6. Barry N, Burton D, Sheridan J, Thompson M, Brown NAT. Aerodynamic drag interactions between cyclists in a team pursuit. *Sports Eng*. 2015;18(2):93-103. doi:10.1007/s12283-015-0172-8
7. Griffith MD, Crouch TN, Thompson MC, Burton D, Sheridan J, Brown NAT. Computational fluid dynamics study of the effect of leg position on cyclist aerodynamic drag. *J Fluids Eng*.

- 2014;136(10):101105. doi:10.1115/1.4027428
8. Achenbach E. Influence of surface roughness on the cross-flow around a circular cylinder. *J Fluid Mech.* 1971;46(2):321-335. doi:10.1017/S0022112071000569
 9. Bearman PW. Investigation of the flow behind a two-dimensional model with a blunt trailing edge and fitted with splitter plates. *J Fluid Mech.* 1965;21(2):241-255. doi:10.1017/S0022112065000162
 10. Havenith G. Heat balance when wearing protective clothing. *Ann Occup Hyg.* 1999;43(5):289-296.
 11. Blocken B, Toparlar Y, Andrianne T. Aerodynamic benefit for a cyclist by a following motorcycle. *J Wind Eng Ind Aerodyn.* 2016;155:1-10. doi:10.1016/j.jweia.2016.04.008
 12. Choi H, Jeon WP, Kim J. Control of flow over a bluff body. *Annu Rev Fluid Mech.* 2008;40:113-139. doi:10.1146/annurev.fluid.39.050905.110149
 13. Bechert DW, Bruse M, Hage W, Van der Hoeven JGT, Hoppe G. Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. *J Fluid Mech.* 1997;338:59-87. doi:10.1017/S0022112096004673
 14. Schlichting H, Gersten K. *Boundary-Layer Theory*. 9th ed. Berlin: Springer; 2017. doi:10.1007/978-3-662-52919-5
 15. Zdravkovich MM. *Flow Around Circular Cylinders. Volume 1: Fundamentals*. Oxford: Oxford University Press; 1997.
 16. Dean B, Bhushan B. Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philos Trans A Math Phys Eng Sci.* 2010;368(1929):4775-4806. doi:10.1098/rsta.2010.0201
 17. Kyle CR, Burke ER. Improving the racing bicycle. *Mech Eng.* 1984;106(9):34-45.
 18. Crouch TN, Burton D, Brown NAT, Thompson MC, Sheridan J. Flow topology in the wake of a cyclist and its effect on aerodynamic drag. *J Fluid Mech.* 2014;748:5-35. doi:10.1017/jfm.2013.678

Figures

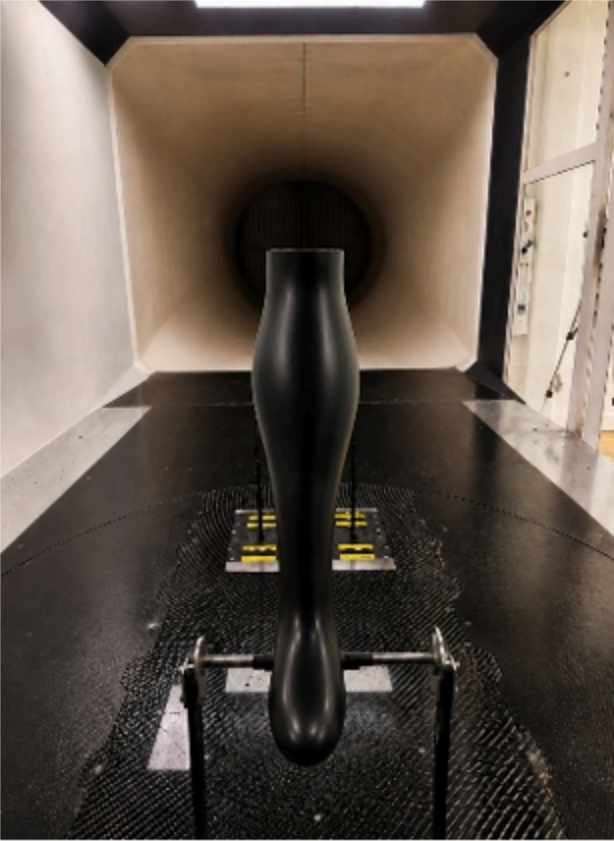


Figure 1

Standardized rigid leg model positioned in a fixed orientation inside the wind tunnel.

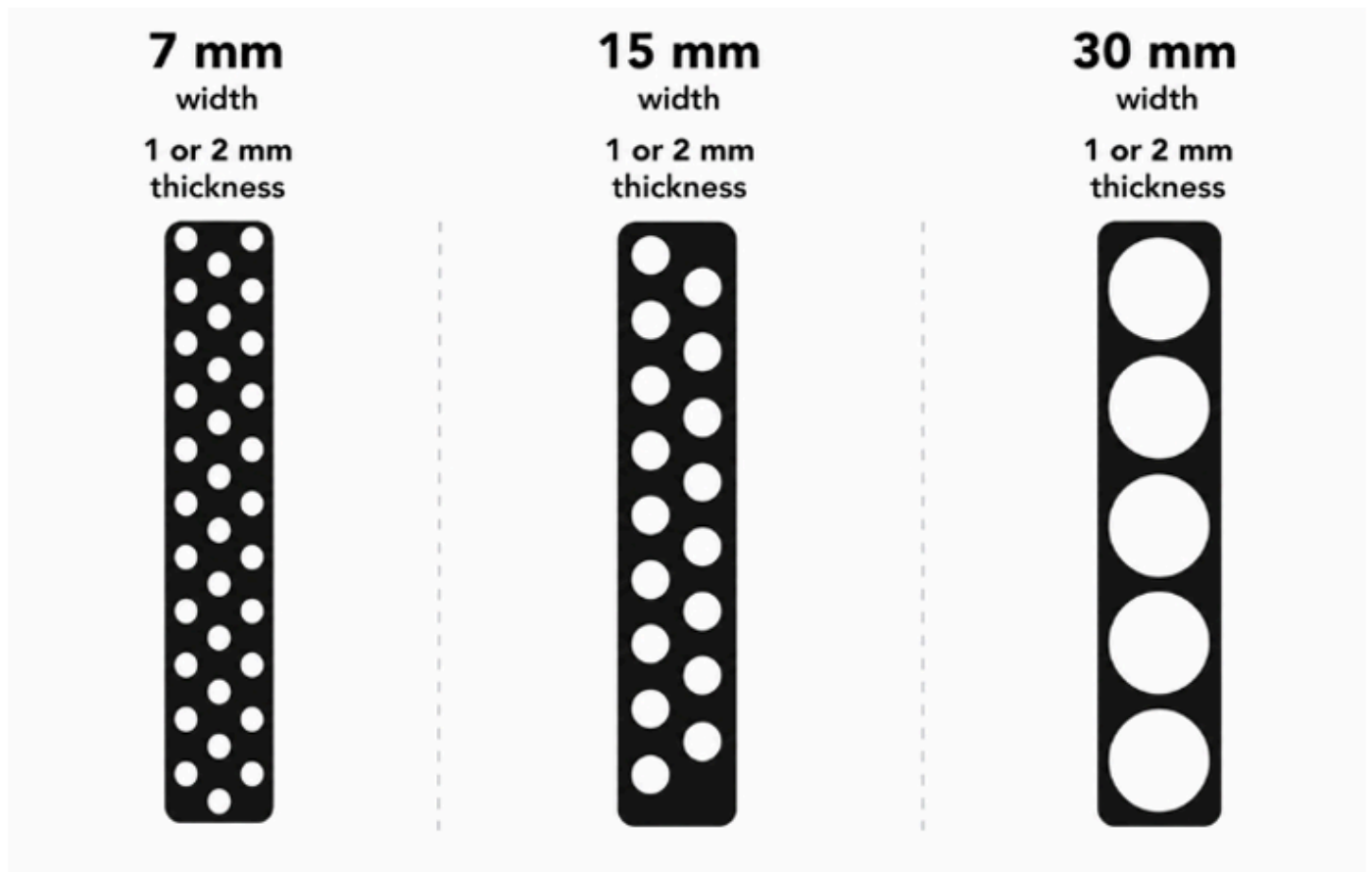


Figure 2

Textured tape configurations evaluated during testing.

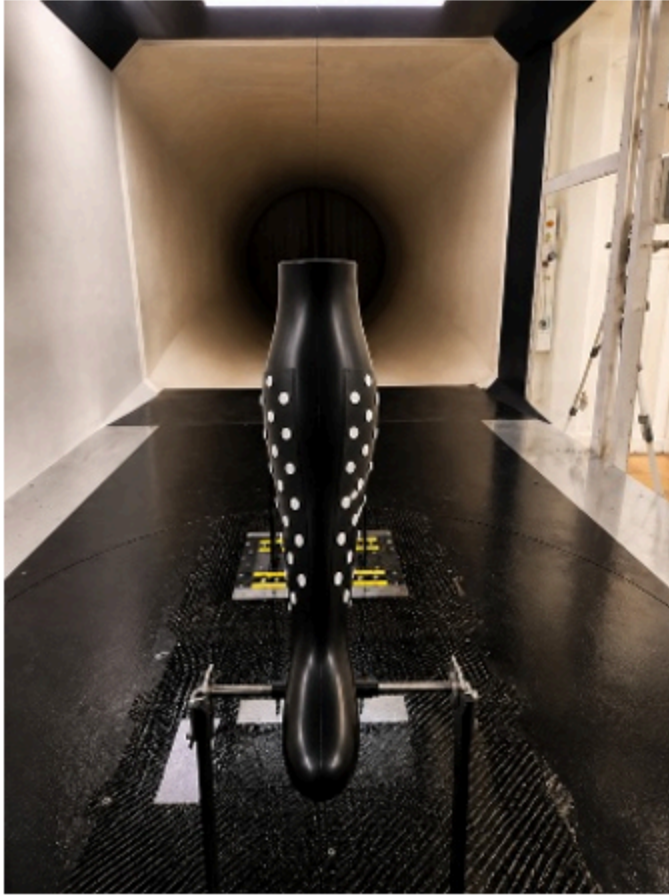


Figure 3

Placement of textured tapes on the rigid leg model.



Figure 4

Aerodynamic calf sleeve used as reference condition.

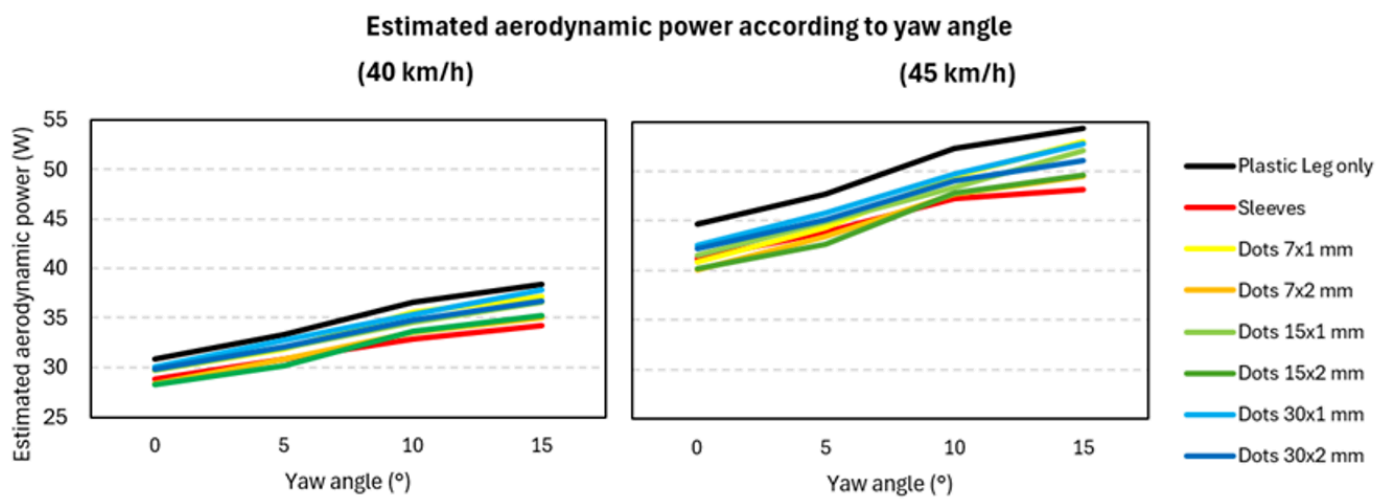


Figure 5

Estimated aerodynamic power requirement as a function of airflow velocity and yaw angle.