Sports Engineering (2026) 29:5
https://doi.org/10.1007/s12283-025-00537-0

REVIEW

Ten questions in sports engineering: generic athlete models for sports fluid dynamics

Knut Erik Teigen Giljarhus[1,2] · **Wouter Terra**[3,4]

Received: 9 July 2025 / Revised: 22 December 2025 / Accepted: 24 December 2025

Abstract

Computational and experimental investigations of flow over athletes are key elements of sports fluid dynamics to analyse performance and equipment design. However, the use of athlete-specific models often limits reproducibility, collaboration, and data sharing due to ethical and competitive constraints. This paper introduces and defines Generic Athlete Models as openly available, standardized geometries accompanied by benchmark flow datasets. The case is made that such models are essential to improve the reliability, comparability, and transparency of fluid dynamics research in sports. While only a few generic athlete models currently exist, this paper outlines clear directions for their further development and broader adoption.

Keywords Aerodynamics · Fluid dynamics · Wind tunnel testing · Computational fluid dynamics · Generic athlete models

1 Introduction

Sports fluid dynamics describes the motion of a fluid, generally air or water, interacting with one or more athletes and their equipment. For a long time, research in this field focused on just measuring the forces acting on the athletes. Facilitated by technical innovation, in the last decade this focus shifted towards understanding the flow around the athlete. Computational Fluid Dynamics (CFD) studies numerically solve the governing equations of fluid flow. Advances in CFD methodology and increased computing power now allow the routine use of athlete models with high morphological detail. In parallel, physical experiments in water channels and wind tunnels employ advanced flow measurement techniques. Methods such as large-scale three-dimensional particle image velocimetry provide deeper insight into the flow around athletes and realistic athlete replicas. These techniques have been applied to a wide variety of sports where fluid-dynamic forces play a pivotal role, including cycling [1–3], running [4], skiing [5, 6], speed skating [7, 8], ski jumping [9] and swimming [10].

The practical nature of sports engineering entails that research groups are often working with sports teams, having access to specific professional athletes. While working with top level athletes may be important for the relevance and quality of the work, this also means that privacy laws and competitive confidentiality hampers sharing and publishing athlete data and research results. The use of anonymous, or generic, athlete geometries, instead, allows researchers to work collaboratively, build a growing knowledge base and publish their datasets (geometric and flow information), without constraints. Recently, some steps have been taken in this direction [11, 12] and, hence, a comprehensible overview and outlook is desired, proving some clarity about what such generic geometries or models are and how they may be used in the future.

This ten-question paper reviews the literature to examine the use of generic models in other industries (Question 1)

Knut Erik Teigen Giljarhus and Wouter Terra have contributed equally to this work.

✉ Knut Erik Teigen Giljarhus
knut.e.giljarhus@uis.no

1 Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, Norway

2 NablaFlow, Stavanger, Norway

3 Department of Aerodynamics, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

4 TeamNL Experts, NOC*NSF, Arnhem, The Netherlands

Published online: 22 January 2026

and to define the concept of a generic athlete model (GAM) (Question 2). Existing GAMs are reviewed, and the most relevant flow characteristics are discussed in relation to human body shape (Questions 3 and 4). The paper then examines the need for GAMs in wind tunnel and CFD comparisons and explains how future wind tunnel experiments can support CFD validation (Questions 5–8). Finally, technologies are discussed that are used to develop GAMs and an outlook is provided on the foreseen evolution of GAMs in the coming years (Questions 9 and 10, respectively).

1.1 How have generic models been useful in other industries?

Generic models have been introduced in other research areas, e.g. the Windsor body and the DrivAer model in the automotive industry and the NASA Common Research Model in the aerospace industry, as shown in Fig. 1. The word model, or body, refers to the geometry of the object. Researchers and industry experts have designed these geometries with the intention of generic usage in mind. The digital geometries are made openly available to everyone via websites [16–18], to be used for experimental and numerical investigations. Physical models are manufactured for experiments in water and air, which have focused, among others, on the development of flow control strategies to optimize aerodynamic performance [19]. Experiment-to-experiment comparisons using generic models have also been used to improve understanding of wind tunnel results, e.g. through initiatives such as the Commonized Automotive Aerodynamic Test Standards (CAATS) [20, 21].

Workshops have been organized to compare numerical results, among each other, and with the experimental benchmark [22, 23]. In the latest automotive CFD prediction workshop, the DrivAer model was simulated by more than 30 different groups with a wide variety of CFD solvers (including OpenFOAM, ANSYS Fluent, Siemens Star-CCM+, Dassault Systèmes PowerFlow, FlexCompute Flow360, Volcano ScaLES, KM-Turbulenz MGLET). The large participation demonstrates the popularity of this approach, and these workshops become important arenas for furthering the field, allowing impartial comparison of results and identifications of areas needing further research.

1.2 What is a generic athlete model compared to a conventional model?

In the current context, a conventional model is defined as an anthropometric realistic geometry of an athlete used for sport fluid dynamics research. Such models have been used for over a decade and are generally obtained by scanning the athlete [24]. Because of ethics and competitive constraints these geometries are rarely shared, hampering others to use them. In contrast to conventional models, GAMs are openly shared to allow others to use them for experimental or numerical investigation and validation. How the use of generic models leads to further insight is discussed in Questions 5 to 8.

A definition of a generic athlete model can be based on the experience with generic models in the automotive and aerospace industry (see Question 1) and the recent work of Terra et al. [12] and Giljarhus and Shaukat [13].

Firstly, a GAM is freely available for everyone, meaning it is published open access. Secondly, the athlete geometry of a GAM is accompanied by a dataset containing the obtained flow information around the geometry. This dataset is also freely available. The GAM and the flow are discussed, and the findings are presented in a peer-reviewed paper, to ensure confidence in the results and to allow other researchers to advance on the work. Thirdly, a GAM has a generic geometry representing a larger population of shapes, in this context a group of athletes. The members that belong to the population may be of the same sport, exhibit similar posture or can be characterised by another feature that significantly differentiates the athlete shape from the overall average. A generic model of a skier, for example, can be an average of a group of females (in contrast to males) down-hill skiers (a skier in slalom is in a different posture). Sport equipment, such as bikes, skis or helmets, may be part of the dataset on GAMs, but these are not generic models by themselves.

Considering the various models used in sports fluid dynamics research, a model hierarchy is proposed, mainly based on an increasing anthropometric realism. The first level, the fluid dynamics canonical cases, such as the circular cylinder and the sphere, exhibit a limited level of realism. The second level of models is closer to a full athlete model but lack some anthropometric realism or completeness, such

Fig. 1 Examples of generic models in other industries. From left to right: The Windsor body [13], the DrivAer body [14] and the NASA Common Research Model [15]

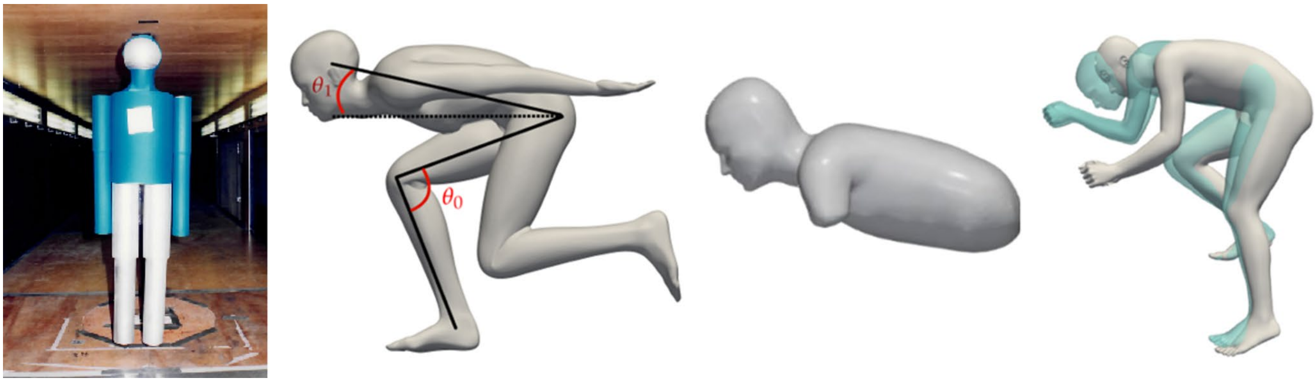

Fig. 2 Cylinder human geometry, reproduced with permission from Len Brownlie (left; [24]) and four Generic Athlete Models (right). The GAMs from left to right: Level 2 GAM of a speed-skater [26]; Level 2 GAM of a head-torso [12]; Level 3 GAM of two cyclists [11]

as building a human model from cylinders as introduced by Brownlie [25]. There are valid reasons to use such models, instead of geometrically more realistic ones, e.g. to simplify manufacturing, simplify numerical simulations or to study the flow around isolated human features. The third, and final GAM level entails models that represent a complete athlete and are anthropometrically realistic. Tests conducted on such models best reproduce the flow over real athletes. Realistic GAMs may therefore also be used for athlete posture optimization and garment testing. However, to what extent these results apply also to individual athletes is yet unknown.

1.3 What generic models and development efforts exist in the field of sports fluid dynamics?

One of the first simplified human models was introduced by Brownlie [25, 26], consisting of an assembly of circular cylinders and a sphere (see Fig. 2-left). It was used to test drag-reducing suits. However, it is not considered a GAM, as its geometry was not made available. If the geometry would have been published, it may have been qualified as a level 1 GAM. To the best knowledge of the authors, only four athlete models have been openly published.

Puelles Magán et al. [27] introduced a speed-skater model which was used for helmet design through numerical simulations (Fig. 2-second). In 2021, the authors published the geometry of the skater and the resulting flow fields. The human model was obtained from an online database available in the MakeHuman software [28]. Subsequently, virtual skeleton methodology (VSM) [29, 30] was used to change the position of the human model into the speed-skating posture. This combination of techniques resulted in a model exhibiting unrealistic anthropometric features, such as a large head and a bulgy chest, hence, it is categorized as a level 2 GAM.

Another proposed model is the head-torso model (Fig. 2-third; Giljarhus and Shaukat [12]) that was introduced for the purpose of CFD validation. The objective was to mimic important flow features related to the head and upper body and have a model that could be used across different sports to enable contributions from more groups. The lack of arms and legs also reduces computational effort but may make the model less suitable for studying the effect of more complex flow interactions, i.e. the effect that one limb has on the flow around another. It was based on a 3D scan of a dummy, combined with averaging multiple athlete geometries that were obtained by scanning individual athletes. The resulting anonymous model is freely accessible, but detailed flow data is currently not shared. Hence it does not fully qualify as a GAM according to the criteria presented here.

Finally, two generic cyclist models (GCMs) were introduced by Terra et al. [11] (Fig. 2-right); one in sprint (or drops) and one in time-trial position. These level 3 GAMs were also obtained through rider scanning and averaging. The specific averaging technique [31] avoids the loss of anthropometric realistic features. The GAM geometry was used to manufacture full-scale wind tunnel models using additive manufacturing. The athlete geometry, the measured flow information and the aerodynamic drag and lift acting on the models are freely accessible [32]. The authors discuss foreseen future variations of the model including management of the models via an open-access online repository.

1.4 What are the relevant flow phenomena in sport fluid dynamics to be considered in the development of generic athlete models?

Many of the features present in the flow over athletes is present as well in flow over concave, rounded, bluff bodies, such as spheres and cylinders. The time-averaged flow over such circular bodies exhibits a wide wake with a large reverse flow, low pressure region [33, 34]. Upstream of the model a high-pressure region exists, while after separation, the pressure is negative, resulting in a large pressure differential and a high pressure drag.

The flow over rounded bluff geometries is governed by the Reynolds number, *Re*, relating the inertial forces to the viscous forces:

$$Re = \frac{\rho V L}{\mu}$$

where V is the velocity, L a characteristic length scale (e.g. the diameter in the case of a cylinder) and ρ and μ the fluid's density and dynamic viscosity, respectively. Within the Reynolds number range applicable to sport fluid dynamics, 10^4 (e.g. arm of marathon runner) to 10^6 (e.g. torso of downhill skier), several flow regimes are observed, governed by the state of the boundary layer [35]. With increasing *Re*, the boundary layer transitions from a laminar state, where the flow exhibits a wide wake and high drag, to turbulence, postponing the point of separation, narrowing the wake and reducing the drag coefficient. This transition process is not only governed by the Reynolds number but also affected by freestream turbulence (see e.g. for cylinder [36], speed-skater [37] and cyclist [38]) and surface roughness (see e.g. for cylinder [39] and cyclist [25]). For a single cylinder or sphere, the transition yields an abrupt and significant reduction in drag, often referred to as the drag crisis. However, in more complex configurations, the effect of transition can be less pronounced.

The human body features a bluff geometry as well, although more complex than that of cylinders and spheres. Depending on athlete posture and orientation, the flow exhibits multiple regions of flow separation e.g. along the hands, arms, head, torso and legs [4, 38, 40, 41]. The separation is affected by flow interactions between the different limbs and by the continuously changing posture of the athlete (e.g. pedalling cyclist [42]), in addition to the aforementioned parameters (Reynolds number, turbulence, roughness). Around athletes that generate lift in addition to drag, such as ski jumpers or a swimmer's hand, the flow exhibits significant downwash opposite to the lift direction. This downwash is accompanied by coherent vortex structures [43], similar to the flow topology of low-aspect-ratio wings.

1.5 How do GAMs help in relating results from different wind and water tunnel facilities?

Measurement of the fluid-dynamic performance of an athlete in a specific condition (e.g. a time-trial cyclist) yields results that differ from experiment to experiment [44]. To some extent these differences can be ascribed to geometrical differences between the models. However, the discrepancy between experiments also stems from differences among the experimental facilities [45]. The most relevant of these are shortly addressed here.

To start with, *the flow uniformity and freestream turbulence* affect the athlete fluid-dynamic performance. The boundary layer, flow separation and, in turn the flow resistance, are particularly sensitive to the latter. Water channels and wind tunnels are typically designed for low freestream turbulence levels: large wind tunnels used for athlete aerodynamic research generally exhibit a turbulence intensity below 2%. A variation of the turbulence intensity within this relatively small 2% range can result in a change of the aerodynamic drag that exceeds 10% [38].

Furthermore, the flow is characterized by the *type and size of the test section* that is bounding the flow around the model. These boundaries cause blockage effects (e.g. solid model blockage, wake blockage, jet/collector blockage) and induce horizontal buoyancy. The former is generally corrected for when the blockage ratio exceeds 3%, which occurs frequently when working with human size bluff bodies in medium size wind tunnels (see e.g. Refs. [5, 46]). Moreover, the flow around the athlete may be altered by measurement instrumentation, such as surface pressure ports and wake rakes [47], and model supports (e.g. to keep a bike upright). Also, measurement error is associated to the operator, the measurement equipment and the measurement procedure, such as observation time, frequency and repeatability.

Altogether, many experimental parameters affect the obtained results. Differences in the results between experiments can be minimized through application of standardized procedures and protocols [48], similar to the CAATS in the automotive industry. The use of a GAM is an important part of such common test protocol. The use of a common athlete geometry should narrow variation in future results among different facilities. Any remaining variations can then be better interpreted and related to the specific experimental conditions, such as turbulence intensity, model orientation, or garment configuration).

1.6 How can we conduct experiments on generic models to aid CFD validation?

In previous sections it has been discussed that the flow around an athlete model is affected by various wind tunnel characteristics and by the Reynolds number, the geometry of the model and its surface properties. To facilitate a consistent comparison of CFD results to experimental work, all these parameters should be measured during experiments so they can be replicated in simulations. Measurements on scaled models should ideally be avoided. Even though dynamic similarity between the experiment and the simulation may be satisfied (increasing wind tunnel speed to account for the smaller model scale), the micro-scale surface properties can generally not be scaled accordingly which can significantly affect the measured overall flow topology.

Experimental work can further aid CFD validation through the measurement of local and whole flow field information. Currently, the fluid-dynamic loads measured experimentally are typically used to validate numerical work. Such integral quantities, however, can lead to false comparisons. There is a risk that models can produce the correct integrated quantity for some cases, while still not simulating the correct flow field. To obtain local flow information instead of integral quantities, various flow measurement techniques are already used in sports fluid dynamics, such as application of pressure taps [47], the use of wake rakes [38, 47] and particle image velocimetry (PIV) [2, 3]. Large-scale 3D PIV, in particular, allows to measure the flow field all around geometrically complex human-scaled models, providing a suitable benchmark for CFD validation. Producing GAM benchmark data requires non-traditional experiments, focused more on the description of boundary conditions and result uncertainty than on obtaining new insights into a specific physical mechanism [50]. The work of Brown et al. [51], comparing the flow in the wake of the 3D printed generic cyclist model in time-trial position obtained in different wind tunnels, can be considered a first step into this direction.

1.7 How can generic models improve the reliability of CFD simulations in sports?

There is currently a large amount of CFD studies performed together with wind tunnel validation. Sensitivity studies are also performed investigating the impact of different turbulence, grids and numerical settings [52].

Simulations are primarily performed on static models with smooth surfaces. The main uncertainties concern the ability of Reynolds-Averaged Navier–Stokes (RANS) models to resolve complex separated flows and boundary layer phenomena, such as laminar-to-turbulent transition [53]. Additional uncertainties arise from the effects of textile roughness [54] and athlete motion on the flow [47]. RANS computes only the mean flow field and uses turbulence models to approximate the effect of all turbulent fluctuations. This makes it computationally efficient but also sensitive to model assumptions in situations where unsteady vortical structures and separation dominate, which is often the case in sports fluid dynamics.

Large Eddy Simulation (LES), in contrast, resolves the major turbulent motions directly and models only the smallest scales. LES can therefore capture unsteady wake dynamics and transient behavior more faithfully than RANS. However, the computational cost of LES remains significantly higher, which limits its widespread use.

While there are examples of validation studies of flow around a single athlete, both using physical athletes [1, 5, 6] and manufactured models [2, 3, 8], there are currently few repeated studies on the same geometry by different research groups. Reproducibility is a critical element of the scientific method, ensuring transparency and robustness, and acts as a safeguard against error, bias, or coincidence.

Generic models will enable multiple groups to work on the same models, leading to higher reliability and trust in CFD simulations. The use of generic models can also lead to a large body of experimental results on the same models, enabling increased insight into where the CFD models perform well and where they need further development.

1.8 What are the next steps in CFD validation in sports fluid dynamics?

As mentioned, the use of LES is currently limited due to computational cost. However, the rapid development of graphics-processing units (GPUs), which are used for training artificial intelligence models, also benefit CFD solvers. This may lead to increased use of such methods, which needs high-quality validation data to compare against. Another recent trend in CFD modelling is uncertainty quantification (UQ). The application of CFD involves both aleatoric (inherent variability) and epistemic (limited knowledge or modelling assumptions) uncertainties, and through parametric studies and statistical methods these can be quantified and controlled. Having standardized benchmark cases relevant to sports engineering would help evaluating the benefits of these emerging technologies.

Moving beyond the current state-of-the-art, some specific sports-related issues in modelling that are still open for research are the behaviour of moving bodies, interactions between the athlete and their equipment and environment, the effect of textiles and vortex generators, and thermoregulation. Generic models will be an important foundation for developing new methodologies and validating models for these phenomena, not only for athletes but also sports equipment.

When developing validation cases for CFD, it is also important to keep the complexity of simulation setup and simulation time in mind. As a comparison, the grid size used for the simplified car model in the most recent AutoCFD workshop was 37 million and 150 million for the detailed car model [55]. Simpler test cases may allow more participation. However, there were also more participants submitting simulations for the detailed model, which may suggest a desire to work on more realistic cases.

1.9 What technologies can assist in the creation of generic athlete validation geometries?

The first step towards a generic validation case is creating a digital generic athlete geometry. In a second step a physical model is manufactured. The digital geometry can be created using published anthropometric data and morphing the human geometry into the desired posture using e.g. VSM. In such cases care need to be taken to avoid non-realistic models [56].

Relatively low-cost handheld scanners, such as Artec Eva (Artec3D, Luxembourg) or ZEISS T-SCAN hawk 2 (Zeiss, Oberkochen, Germany), can create high-quality, detailed models of a full-body athlete. One issue of this method is the need for the athlete to remain stationary for up to several minutes, which is demanding on them and may decrease accuracy. A faster method is to use photogrammetry, i.e. multiple cameras, which are now increasingly becoming available, e.g. Artec Shapify Booth or botspot FLEX (botspot 3D Scan, Berlin, Germany). Once multiple bodies are obtained, these can be combined into a generic model by averaging multiple models [11]. Using techniques like the VSM, these generic models can also be further modified to study e.g. different leg positions, or to investigate the sensitivity of the position to the performance.

There are also emerging AI methods to construct 3D models from a limited number of pictures [57, 58], as well as pose databases such as SportsPose [59]. Additionally, there are general human body shapes created for computer vision, such as the Skinned Multi-Person Linear Model (SMPL) [60], that can potentially be adapted to sports poses. Currently the training data used for these AI methods and the poses in these databases do not contain typical aerodynamic postures, but there are promising recent developments [61].

Finally, to create physical GAMs for experimental testing, the same techniques can be employed as to manufacture conventional anthropometrically realistic athlete models, e.g. computer numerical controlled (CNC) milling [38] and additive manufacturing [12].

1.10 What are the next steps in generic model generation and application?

There are several relevant steps in further development and use of GAMs; improvement of numerical and experimental techniques, development of new and improved GAMs, and application of GAMs to further understand sports fluid dynamics.

The application of GAMs in validation of numerical simulations is particularly relevant. The published generic cyclist model and the experimentally measured flow around it can be used for the validation of numerical simulations. Workshops may be organized, like initiatives in other industries, focusing on validation within sports engineering to bring together different research groups. As additional data become available for a GAM, existing data repositories may be extended in a controlled manner to enrich the dataset. This approach preserves traceability, consistency, and reproducibility across dataset versions.

Development of new models are also foreseen, as discussed in the work on the Generic Cyclist Model [11], for example a female cyclist model, to understand the impact of gender anthropometric differences on the flow, and models in other sports than cycling.

An important question in future development is to find the appropriate level of generalization. This is not always clear *a-priory*, e.g. a group of athletes with particularly long legs may exhibit significantly different aerodynamic characteristics than the average. If it can be demonstrated that leg-length is a differentiating characteristic of an athlete, a new generic model may be introduced. Terra et al. [11] suggest that the cyclist's shoulder width significantly governs the wake topology. If this can be demonstrated this may potentially lead to a new GAM.

Instead of introducing new generic models, modifications and additions to an existing model are also possible. Giljarhus and Shaukat [12] suggest using VSM to make small modifications to the human shape. This method allows to make changes to the outer shape of the GAM by rigging the individual bones that are introduced inside the geometry in e.g. Blender etc. VSM can also be used to find the position of an athlete that results in the optimal aerodynamic characteristics [62]. For small changes in position, it seems unnecessary to introduce a new model. Potential new developments related to VSM, increasing the level of realism, include improved skinning method, such as Dual Quaternion Skinning [63], and more realistic muscle behaviour through muscle simulation systems [64].

Finally, a challenge lies in the development of moving GAMs to develop a better understanding of the effects of these unsteady body motions on the fluid dynamic performance. One aspect is the replication of the human soft tissue [65], which would allow to produce an anthropometric realistic moving GAM.

2 Discussion

Current GAMs are still sparse in diversity, i.e. sports activity, gender, body type, and motion states, with only the speed-skater model and the cyclist model (both male) satisfying the criteria put forth by the authors. The success of generic models in other industries suggests that the use of GAMs can promote our understanding of the flow around human athletes, through the ability to work on the same model, reproduce each other's results and advance it. GAMs are free to use for everyone and, upon introduction, accompanied by a peer-reviewed paper and an open-access flow dataset. This allows to ascribe differences in experimental results among various facilities to the specific features of those facilities and provides a benchmark database for qualitative CFD validation. The availability of GAMs also provides researchers with high quality reference data, that they would otherwise not have been able to obtain. The availability of GAMs also allows researchers to advance the sports fluid dynamics knowledge by focusing on their specific research topics and not having to create reference data themselves.

Creating anthropometric realistic yet generic models require balancing simplification with realism, poses challenges in model generation and requires careful thinking of the specific purpose of the GAM: an over-simplified generic model may not exhibit the flow features of the parent athletes, while a too detailed model may hamper adoption for numerical applications. Careful consideration is required by the scientific community, when deciding whether to adopt a new GAM or to introduce an adaptation of an existing one; an abundance of all kinds of different GAM flavours seem undesirable and may become confusing. A central storage location and an overarching storage structure for all GAMs may provide the necessary overview and clarity that avoids such overgrowth.

Moreover, building a GAM database requires a different type of experiment; one that is specifically designed for the purpose of benchmarking and aims to obtain whole-field flow data instead of integral quantities.

Future work should expand the GAM library to other sports and athlete demographics. Collaborative validation workshops, similar to those in the aerospace and automotive fields, would strengthen benchmarking practices and accelerate progress. Anthropomorphic realistic moving human models would allow to extent the database for cases where unsteady flow features dominate athlete fluid-dynamic performance. Finally, extending the GAM approach to sport-specific equipment and apparel could also yield valuable insights beyond the athlete body alone.

3 Conclusion

This paper has attempted to define generic athlete models (GAMs) in the context of sports engineering. Key takeaways include the importance of full-body, anthropometric realism; the benefits of open-access, peer-reviewed data; and the potential for GAMs to serve as shared references for CFD validation and experimental benchmarking. GAMs are an important development to improve reproducibility, collaboration, and reliability in sport fluid dynamics.

Author contributions All authors whose names appear on the submission—made substantial contributions to the conception or design of the work—drafted the work and revised it critically for important intellectual content;—approved the version to be published; and—agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Funding Open access funding provided by University of Stavanger & Stavanger University Hospital

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

References

1. Defraeye T, Blocken B, Koninckx E, Hespel P, Carmeliet J (2010) Aerodynamic study of different cyclist positions: CFD analysis and full-scale wind-tunnel tests. J Biomech 43:1262–1268
2. Jux C, Sciacchitano A, Schneiders JF, Scarano F (2018) Robotic volumetric PIV of a full-scale cyclist. Exp Fluids 59:1–15
3. Terra W, Sciacchitano A, Shah YH (2019) Aerodynamic drag determination of a full-scale cyclist mannequin from large-scale PTV measurements. Exp Fluids 60:29
4. Schickhofer L, Hanson H (2021) Aerodynamic effects and performance improvements of running in drafting formations. J Biomech 122:110457
5. Elfmark O, Giljarhus KET, Liland FF, Oggiano L, Reid R (2021) Aerodynamic investigation of tucked positions in alpine skiing. J Biomech 119:110327
6. Giljarhus KET, Reid R, Liland FF, Oggiano L, Elfmark O (2022) Aerodynamic influence of an alpine skier's arms. Sports Eng 25:20
7. Spoelstra A, Terra W, Sciacchitano A (2023) On-site aerodynamics investigation of speed skating. J Wind Eng Ind Aerodyn 239:105457

8. Zhang Y, Li B (2024) Aerodynamic drag characteristics of skaters in speed skating team pursuit formation. Eur J Mech B Fluids 103:116–125
9. Kim W, Lee H, Lee J, Jung D, Choi H (2019) Flow over a ski jumper in flight: prediction of the aerodynamic force and flight posture with higher lift-to-drag ratio. J Biomech 89:78–84
10. Cohen RC, Cleary PW, Mason BR (2015) The role of the hand during freestyle swimming. J Biomech 48:4197–4203
11. Terra W, Brown C, Vloemans S, van der Waals M, Sciacchitano A, Burton D, Thompson MC, Huysmans T (2024) A generic cyclist model for aerodynamic investigation: design, geometry & first aerodynamic analysis of a male time-trial and sprint model. J Wind Eng Ind Aerodyn 252:105829
12. Giljarhus KET, Shaukat U (2024) Flow simulation of a simplified athlete geometry using partially-averaged Navier-Stokes. In: ISEA 2024, The Engineering of Sport 15, Loughborough University, UK
13. Varney M (2019) Base drag reduction for squareback road vehicles. PhD thesis, Loughborough University
14. Heft AI, Indinger T, Adams NA (2012) Introduction of a new realistic generic car model for aerodynamic investigations. SAE Technical Paper 2012–01–0168
15. Vassberg JC, DeHaan MA, Rivers MB, Wahls RA (2008) Development of a common research model for applied CFD validation studies. AIAA Paper 2008–6919
16. NASA (2022) NASA Common Research Model. https://commonresearchmodel.larc.nasa.gov/
17. National Wind Tunnel Facility (2024) Windsor automotive reference model. https://www.nwtf.ac.uk/dataset/1709/
18. Technical University of Munich (2025) DrivAer. https://www.epc.ed.tum.de/en/aer/research-groups/automotive/drivaer/
19. Lin JC, Melton LG, Viken S, Andino MY, Koklu M, Hannon J, Vatsa VN (2017) High lift common research model for wind tunnel testing: an active flow control perspective. 55th AIAA Aerospace Sciences Meeting AIAA 2017–0319
20. Bringhurst K, Walter J, Best S, (2024) CAATS–automotive wind tunnel statistical process control (No. 2024–01–2542). SAE Technical Paper
21. Bringhurst K, Best S, Esfahani VN, Senft V, Stevenson S, Wittmeier F, (2025) CAATS–automotive wind tunnel calibrations (No. 2025–01–8762). SAE Technical Paper
22. Ashton N, van Noordt W (2023) Overview and summary of the first Automotive CFD prediction workshop: DrivAer model. SAE Int J Commer Veh 16:61–85
23. Levy DW, Zickuhr T, Vassberg J, Agrawal S, Wahls RA, Pirzadeh S, Hemsch MJ (2003) Data summary from the first AIAA computational fluid dynamics drag prediction workshop. J Aircraft 40:875–882
24. Chi S, Pitman J, Crouch T, Burton D, Thompson M (2021) The application of body scanning, numerical simulations and wind tunnel testing for the aerodynamic development of cyclists. Proc Inst Mech Eng Pt P J 235(4):339–353
25. Brownlie L (1993) Aerodynamic characteristics of sports apparel. PhD thesis, National Library of Canada
26. Brownlie L, Kyle C, Carbo J, Demarest N, Harber E, MacDonald R, Nordstrom M (2009) Streamlining the time trial apparel of cyclists: the Nike Swift Spin project. Sports Technol 2:53–60
27. Puelles Magán G, Terra W, Sciacchitano A (2021) Aerodynamics analysis of speed skating helmets: investigation by CFD simulations. Appl Sci 11:3148
28. MakeHuman—Open Source Tool for Making 3D Characters. (2020) Available online: http://www.makehumancommunity.org
29. Magnenat-Thalmann N, Laperriere R, Thalmann D (1988) Joint-dependent local deformations for hand animation and object grasping. Tech Rep, Canadian Inf Process Soc
30. Giljarhus KET, Liland FF, Oggiano L (2023) Virtual skeleton methodology for athlete posture modification in CFD simulations. Sports Eng 26(1):39
31. Huysmans T, Goto L, Molenbroek J, Goossens R (2020) DINED mannequin. Tijdschr Hum Factors 45:4–7
32. Terra W, Brown C, Vloemans S, van der Waals M, Sciacchitano A, Burton D, Thompson MC, Huysmans T, (2024) Data underlying the publication**:** a generic cyclist model for aerodynamic investigation: design, geometry & first aerodynamic analysis of a male time-trial and sprint model. 4TU Repository. https://doi.org/10.4121/a6bafb56-588e-40cd-a304-4a1cd61a312d
33. Achenbach E (1968) Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re = 5 x 10^6. J Fluid Mech 34(4):625–639
34. Achenbach E (1972) Experiments on the flow past spheres at very high Reynolds numbers. J Fluid Mech 54(3):565–575
35. Zdravkovich MM (1997) Flow around circular cylinders. Vol I: Fundamentals. Oxford Science Publications
36. Norberg C, (1987). Effects of reynolds number and low-intensity freestream turbulence on the flow around a circular cylinder. Chalmers University of Technology, Department of Applied Thermodynamics and Fluid Mechanics, Technical Report, May 1987
37. D’Auteuil A, Larose GL, Zan SJ (2012) Wind turbulence in speed skating: measurement, simulation and its effect on aerodynamic drag. J Wind Eng Ind Aerod 104–106:585–593
38. Brown C, Burton D, Crouch T, Thompson MC (2023) The influence of turbulence on cycling aerodynamics. J Wind Eng Ind Aerodyn 242:105575
39. Achenbach E (1971) Influence of surface roughness on the cross flow around a cylinder. J Fluid Mech 46(2):321–335
40. Van der Berg J, Bazuin R, Jux C, Sciacchitano A, Westerweel J, van de Water W (2021) The effect of hand posture on swimming efficiency. Exp Fluids 62:245
41. Blocken B, Malizia F, Laguna P, Marshall D, Bell D, Marchal T (2024) Numerical-physical modelling of the long jump flight of female athletes: impact of jump style, hairstyle and clothing. J Wind Eng Ind Aerodyn 252:105837
42. Crouch TN, Burton D, Thompson MC, Brown NAT, Sheridan J (2016) Dynamic leg-motion and its effect on the aerodynamic performance of cyclists. J Fluid Struct 65:121–137
43. Yamamoto K, Tsubokura M, Ikeda J, Onishi K, Baleriola S (2016) Effect of posture on the aerodynamic characteristics during take-off in ski jumping. J Biomech 49:3688–3696
44. Crouch TN, Burton D, LaBry ZA, Blair KB (2017) Riding against the wind: a review of competition cycling aerodynamics. Sports Eng 20:81–110
45. Barlow JB, Rae WH, Pope A (1999) Low speed wind tunnel testing. Wiley, New York
46. Blocken B, van Druenen T, Topolar Y, Malizia F, Mannion P, Andrianne T, Marchal T, Maas G, Diepens J (2018) Aerodynamic drag in cycling pelotons: new insights by CFD simulation and wind tunnel testing. J Wind Eng Ind Aerodyn 179:319–337
47. Crouch TN, Burton D, Brown NAT, Thompson MC, Sheridan J (2014) Flow topology in the wake of a cyclist and its effect on aerodynamic drag. J Fluid Mech 748:5–35
48. Brownlie LW (2019) Wind tunnels: design considerations in wind tunnel testing of cyclists. Biomechanical principles and applications in sports. Springer International Publishing, Cham, pp 57–86
49. Griffith MD, Crouch T, Thompson MC, Burton D, Sheridan J, Brown NA (2014) CFD study of the effect of leg position on cyclist aerodynamic drag. J Fluids Eng 136:101105
50. Smith WL (2017) The difference between traditional experiments and CFD validation benchmark experiments. Nucl Eng Des 312:42–47

51. Brown C, Terra W, Sciacchitano A, van der Waals M, Huysmans T, Thompson MC, Burton D (2024) Towards a benchmark velocity database of a Generic Cycling Mannequin. In: ISEA 2024—The Engineering of Sport 15, Loughborough University, UK
52. van Druenen T, Blocken B (2024) CFD simulations of cyclist aerodynamics: impact of computational parameters. J Wind Eng Ind Aerodyn 249:105714
53. Walker AD, Butcher D, Crickmore C, Taylor M (2024) Practical CFD predictions of a cyclist in a time trial position. J Wind Eng Ind Aerodyn (in press)
54. Oggiano L, Brownlie B, Troynikov O, Bardal LM, Sætran L (2013) A review on skin suits and sport garment aerodynamics: guidelines and state of the art. Procedia Eng 60:91–98
55. AutoCFD (2024). 4th Automotive CFD Prediction Workshop. https://autocfd.org/autocfd4/. Accessed 30 November 2025
56. Garimella R, Beyers K, Huysmans T, Verwulgen S (2020) Rigging and Re-posing a human model from standing to cycling configuration. In: Advances in Additive Manufacturing, Modeling Systems and 3D Prototyping. AHFE 2019, Advances in Intelligent Systems and Computing, 975
57. Saito S, Simon T, Saragih J, Joo H (2020) PIFuHD: Multi-level pixel-aligned implicit function for high-resolution 3D human digitization. Proc CVPR:84–93
58. Corona E, Pons-Moll G, Alenya G, Moreno-Noguer F (2022) Learned vertex descent: a new direction for 3D human model fitting. Eur Conf Comput Vis:146–165
59. Ingwersen CK, Mikkelstrup CM, Jensen JN, Hannemose MR, Dahl AB (2023) Sportspose - a dynamic 3D sports pose dataset. Proc CVPR:5219–5228
60. Loper M, Mahmood N, Romero J, Pons-Moll G, Black MJ (2023) SMPL: a skinned multi-person linear model. Seminal Graphics Papers 2:851–866
61. Chen X, Chu FJ, Gleize P, Liang KJ, Sax A, Tang H, Wang W, Guo M, Hardin T, Li X, Lin A (2025) SAM 3D: 3Dfy Anything in Images. arXiv preprint arXiv:2511.16624
62. Giljarhus KE, Liland FF, Bardal LM, Oggiano L (2024) Aerodynamic optimization of athlete posture using virtual skeleton methodology and computational fluid dynamics. J Biomech 176:112303
63. Kavan L, Collins S, Žára J, O'Sullivan C (2007) Skinning with dual quaternions Proc I3D:39–46
64. van Bijlert PA (2024) MuSkeMo: Open-source software to construct, analyze, and visualize musculoskeletal models in Blender. bioRxiv 2024–12.
65. Holzapfel GA, Ogden RW (2025) Modelling the biomechanical properties of soft biological tissues: constitutive theories. Eur J Mech A Solids 112:105634