ACTA OF BIOENGINEERING AND BIOMECHANICS
Vol.24, no.2, 2022 - in press, consultado em 14set22
https://www.actabio.pwr.wroc.pl/24322.php

**DOI: 10.37190/ABB-02019-2022-06**

# Aerodynamic analysis of human walking, running and sprinting by numerical simulations

Pedro Forte[1,2,3*], Nuno Sousa[4], José E. Teixeira[2,3,5], Daniel A. Marinho[3,6], António M. Monteiro[2,3], José A. Bragada[2,3], Jorge E. Morais[2,3], Tiago M. Barbosa[2,3]

[1]Department of Sports, Instituto Superior de Ciências Educativas do Douro, Penafiel, Portugal;
[2]Department of Sports Sciences, Instituto Politécnico de Bragança, Bragança, Portugal;
[3]Research Center in Sports, Health and Human Development (CIDESD), Covilhã, Portugal;
[4]Department of Arts and Multimedia, Instituto Superior de Ciências Educativas do Douro, Penafiel, Portugal;
Portugal;
[5]Department of Sports, Exercise and Health Sciences, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal;
[6]Department of Sports Sciences, University of Beira Interior, Covilhã, Portugal.

*Corresponding author: Pedro Forte, Research Centre in Sports Sciences, Health and Human Development (CIDESD), Quinta de Prados, 5000-801, Vila Real, Portugal, email address: zeteixeira1991@gmail.com

**Founding:** This project was founded by the Portuguese Foundation for Science and Technology, I.P. (project UIDB04045/2020).

Submitted: 31st January 2022
Accepted: 18th July 2022

## Abstract

The drag in walking, running, and sprinting locomotion can be assessed by analytical procedures and experimental techniques. However, assessing the drag variations by these three main locomotion's (i.e., walking, running, and sprinting) were not found using computational fluid dynamics. (CFD). Thus, the aim of this study was two-fold: (1) to assess the aerodynamics of human walking, running, and sprinting by CFD technique; 2) compare such aerodynamic characteristics between walking and running. Three 3D models were produced depicting the walking, running, and sprinting locomotion techniques, converted to computer aided design models and meshed. The drag varied with locomotion type. Walking had the lowest drag, followed-up by running and then sprinting. At the same velocities, the drag was larger in walking than in running and increased with velocity. In conclusion, drag varied with locomotion type. Walking had the lowest drag, followed-up by running and then sprinting. At the same velocities, the drag was larger in walking than in running and increased with velocity.



**Keywords:** Locomotion; CFD; Drag; Comparison; Aerodynamics.

# Introduction

Human locomotion is one of the main topics of research in biomechanics [13]. Higher ability to walking and running [11], and jumping or squatting enhances a subject's physical capacity [36]. Generally, walking is used to move at low speed and running is used for faster movement. The "natural" walking speed in adults is close to 1.4 m/s [9]. In the speed range between 1.38 and 2.22 m/s the transition to running usually occurs [9,36]. However, walking competitions may be up to 4.17 m/s in elite athletes.

Walking is generally distinguished from running in that only one foot at a time leaves contact with the ground and there is a period of double-support [40]. In contrast, running begins when both feet are off the ground with each step. Running can be used over a huge speed range; sprinting usually refers to running at maximum speed, which consequently can only be used over very short periods of time [21,40]. The average speed of the current 100m running world record is 10.43 m/s [38]. Fukuchi et al. [38] in a systematic review found "that speed affected the gait patterns of different populations with respect to the amplitude of spatiotemporal parameters, joint kinematics, joint kinetics, and ground reaction forces. Specifically, most of the values analyzed decreased at slower speeds and increased at faster speeds".

It has been reported that human running activity is more economical (i.e., leads to less energy expenditure) in comparison to walking at a given velocity [29]. Upon that, it is important to better understand the human locomotion. Scientists and analysts seek as much information as possible [30]. In literature, it is possible to find forecasts and comparisons between high-performance athletes [1], running efficiency analysis [34], physiological stress assessment [26], kinematic [13] and kinetic analyses [10]. That said, it is important to describe the factors that may explain the differences of land human locomotion techniques.

Over time, research was keen on assessing the resistance acting on an athlete during a race [6]. Drag ($F_d$) is considered as one of the mechanical determinants underlying the human locomotion performance [1], [25], [26], [34]. It may contribute between 3% and 16% to the runner resistance and/or energy cost [25]. Nevertheless, it is important to improve the data information about land human locomotion, about drag variations for walking, running, and sprinting. That will allow to explain the differences between human locomotion regarding economy and performance.

The drag is typically dependent of velocity (drag: equation 1), the surface area, and the coefficient of drag (equation 2) is the variable that characterize the aerodynamic profile [17].

$$F_d = \frac{1}{2}\rho A C_d v^2 \quad (1)$$

$$C_d = \frac{F_d}{\frac{1}{2}\rho A C_d v^2} \quad (2)$$

Where, $F_d$ is the drag, ρ is the air density, A is the surface area, $C_d$ is the drag coefficient and v is the velocity.

Moreover, the coefficient of drag is dependent of Reynolds number (Re: equation 3). Finally, $R_e$ (equation 4) is dependent of the body length (L), fluid flow velocity (U), air density (p) and fluid dynamic viscosity (μ).

$$C_d = f(Re) \quad (3)$$

$$R_e = \frac{\rho L U}{\mu} \quad (4)$$

Based on equations 1 to 4 the body positions will affect the surface area, body length and fluid flow. These variations have already been studied in parasports [14], [19], [20], and cycling [16], [21]. Drag is expected to increase with speed and the variations will depend of the human locomotion type. Walking is performed at lower speeds than running and sprinting (being sprinting the fastest). Thus, it is expected that the drag will be lower at walking, followed by running and sprinting. However, it is possible to walk or run for a short range of velocities (2.22 m/s and 4.17 m/s) and no study was found comparing the drag variations for these two conditions. Analysing the drag variations by locomotion type and velocities will allow to better understand the locomotion economy and its possible contribution to sportsmen performance [25]. That said, describing the drag variations by locomotion type and velocity will be a highly valued topic to scientific community.

The drag in different types of locomotion can be assessed by analytical procedures [10], experimental techniques, such as wind tunnel [25] and numerical simulations [4]. However, assessing the drag variations by these three main locomotion's (i.e., walking, running, and sprinting) were not found. In wind tunnel analysis, only drag coefficient was reported [25]. The estimations by analytical procedures do not control individual and environmental factors [6]. At least one study was founded assessing an athlete's drag by numerical simulations [4]. However, the authors only reported the pressure maps and pressure coefficients at 5.88 m/s. No study was founded assessing an athlete's drag at different speeds. On top of that, to author's best knowledge, no study was founded assessing pressure, viscous and total drag in walking condition.

The numerical simulations by computer fluid dynamics (CFD) are presented as a valid and precise method in different sports such as cycling [4], [6], [16], [21], [39], ski-jumping [24] and wheelchair [22], [27]. The CFD presented concordant data in comparison with both analytical procedures and experimental testing [3], [18]. This methodology allows to assess the fluid flow behaviour around an athlete and control environmental conditions such as temperature and/or wind conditions [22]. Moreover, CFD allow to output data such as pressure, viscous and total drag [17]. The pressure drag is given by the pressure differences between the athlete front and back boundaries and in different sports has presented a higher contribution to total drag [21]. The viscous drag results from the interaction between the athlete and the fluid, where the fluid gets dragged to the athlete body, as less the fluid dragged to the athlete, less the viscous drag [3], [17]. This methodology has been used with scanned participants into 3D models as the abovementioned studies. However, recent methodologies have created three dimensional geometries, representative of the real objects [18]. To the authors' best knowledge, this will be the first study with a human body three-dimensional created geometry.

Therefore, the aim of this study was to: (1) assess an athlete's aerodynamic characteristics in walking, running, and sprinting at different velocities, and; (2) compare such aerodynamic characteristics between walking and running. It was hypothesized that drag increases with speed, by human locomotion type, and that the walking drag would present higher values in comparison to running for the same velocities.

## Methods

*Participant*

A recreational male runner was recruited to participate in this research. The subject had 78 kg of mass, 1.83 m of height and 8 years of background in running. He was a recreational runner competing at local and national events such as mini, half and full marathons. An informed written consent was obtained beforehand. All the procedures were in accordance with Helsinki's declaration regarding research with human beings. The scientific committee of the Douro Higher Institute of Educational Sciences approved this research.

*3D model*

A male human representative 3D model was created with Blender (Blender 2.92, Blender Foundation, Amsterdam, Netherlands) based on the participant anthropometrics. A static walking position (Figure 1, left panel) was created. The geometry was exported as a stereolithography (*.stl*) file. The stl file was then imported to Geomagic Studio (3D System, Rock Hill, SC, USA) and corrections such as pikes reduction, smoothing and correct self-intercept faces were made. Upon that, the geometry was exported as a computer-aided design (CAD) model.

Based on the walking 3D geometry, a running (Figure 1, middle panel) and sprinting (Figure 1, right panel) models were created on Blender software (Blender Foundation 2.91.0, Amsterdam, Netherlands). The geometries were created in the mid-stance [3]. The walking participant CAD model was re-converted and exported to object (.obj) on Geomagic Studio (2013, 3D System, Rock Hill, SC, USA). This procedure was conducted because the original file was edited and corrected, then to obtain the final CAD model was obtained. The blender software allowed to create a skeleton for the arms, legs and torso. Thereafter, the shoulders, elbows, hips, knees and ankles were rotated. Thus the running model was obtained by changing the joints relative angles. Then, the geometry was exported as *.stl*, imported into Geomagic Studio where, after correction a CAD model of the running participant was created.

Figure 1. Walking, running and sprinting participant 3D geometries.

*Boundary Conditions*

On Ansys Design Module software (Ansys Workbench 16.0, Ansys Inc., Pennsylvania, PA, US), an enclosure (domain) was created with 4 m length, 4 m width and 4 m heigh. The geometry was placed at 1 m of distance from the inlet portion of the domain (Figure 2). Then, the Boolean option subtracted the geometry from the domain, and the void was considered as a wall. After this procedure, the process was carried out on Ansys Meshing Module.

Figure 2. Domain around the geometry of the walking participant.

The surface area of the current computational domain has considered the CFD's criteria of the practice guidelines [8], [33] (figure 3). The domain was meshed with more than 42 million elements to represent the fluid as mentioned in previous reports [21]. The elements were prismatic and tetrahedral with cell size near 25.72 µm. The cyclist geometry was at 2.5 m from the inlet portion for each simulation.

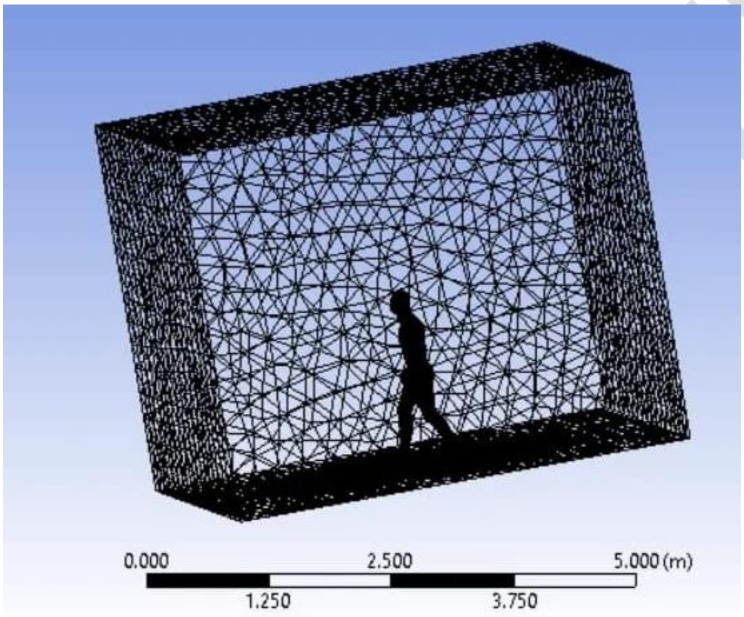


Figure 3. Projected surface area of the participant 3D model

The Ansys Meshing Module, enabled to generate a mesh/grid on the domain to represent the fluid around the runner. The domain was split with 4 million of prismatic and pyramidal elements. Near the runner boundaries a refined mesh was created based on automatic mesh settings. The final grid was chosen based on skewness, orthogonal quality, amount of elements and Y+ wall turbulence values. The mesh was fine near the athlete and coarser farther away from the model. That allowed to obtain accurate flow results near the athlete. The "proximity" and "curvature" options were selected for the grid generation. The best quality mesh was created with the "proximity and curvature" option. The high ‘smoothing’ and a program-controlled ‘inflation’ setting were defined on the mesh generation.

*Numerical Simulations*

The Ansys Fluent Module (Ansys Workbench 16.0, Ansys Inc., Pennsylvania, PA, US) enables to solve the Reynolds-Average-Navier-Stokes equations. The Fluent CFD code, allows to transform instantaneous values into means by the finite volume method, introducing new variables from the turbulence models [18], [35]. In Fluent the available turbulence models are the standard k-epsilon, realizable k-epsilon, RNG and RST. In the present study the realizable k-epsilon turbulence model was chosen due to the computation economy provided [15]. At speeds below 2.22 m/s the laminar fluid flow was used. Realizable k-epsilon turbulence model was proceed using a RANS model based on previous cycling studies [18], [21]. Moreover, the Realizable k-epsilon showed higher computation economy in comparison to Standard k-epsilon, RST and RNG k-epsilon models [17], [19], [31].

The numerical simulations to assess drag were run between 0.28 m/s and 11.11 m/s, with increments of 0.28 m/s. Typically, during sprinting events, athletes may reach the top speeds selected in this study [1]. At the inlet portion of the domain (-z direction), each speed was selected for the numerical simulations. The turbulence intensity was set as $1 \times 10^{-6}$%, and the athlete was set with the scalable walls function [27]. The walking condition drag was assessed up to 4.17 m/s, the running condition between 4.17 m/s and 6.39 m/s and, sprinting between 6.67 m/s and 11.11 m/s. The turbulence intensity was used based on previous studies [15], [37].

The SIMPLE algorithm was used for pressure-velocity coupling [15]. The convection terms, pressure and viscosity were defined as second order and the least squares cell-based technique computed the gradients [15], [31]. The moment and pressure were computed as first and second orders, respectively. The turbulent kinetic energy was set as first order upwind.

*Outputs*

After each simulation at a given velocity, drag (pressure drag, viscous drag and total drag) was extracted from the Ansys Fluent Software (Ansys Fluent 16.0, Ansys Inc., Pennsylvania, USA). The coefficient of drag (pressure, viscous and total) was also extracted from the software [21].

The pressure drag ($F_{dp}$) and the viscous drag ($F_{dv}$) are expressed as:

$$F_{dp} = \frac{1}{2}\rho A C_{dp} v^2 \quad (5)$$

$$F_{dv} = \frac{1}{2}\rho A C_{dv} v^2 \quad (6)$$

Total drag was the sum of pressure and viscous drag components.

The pressure and viscous coefficient of drag are expressed as:

$$C_{dp} = \frac{0.5pAv^2}{F_{dp}} \quad (7)$$

$$C_{dp} = \frac{0.5pAv^2}{F_{dp}} \quad (8)$$

The total coefficient of drag was the sum of pressure and viscous coefficients.

*Statistical analysis*

Descriptive statistics, Shapiro-Wilk and Levene's tests were selected to assess normality and homogeneity. The drag value between running and walking for the 8 velocities (between 2.22 m/s and 4.17 m/s with increments of 0.28 m/s). Power curve estimation models for each condition were computed to determine the total drag trendline. Effect sizes were set as very weak if $R^2 < 0.04$, weak if $0.04 \leq R^2 < 0.16$, moderate if $0.16 \leq R^2 < 0.49$, high if $0.49 \leq R^2 < 0.81$ and very high if $0.81 \leq R^2 < 1.0$ [27]. For all the tests, the statistical significance was set at 5%.

**Results**

The results are presented for descriptive analysis of drag coefficients (pressure, viscous and total) and drag variations and contributions (pressure and viscous drag contribution to total drag by locomotion technique and across the different velocities. Afterwards, the drag coefficients and drag force comparisons between walking and running are presented.

*Drag coefficients and drag forces descriptive analyses*

Figure 4 depicts the drag coefficients (pressure, viscous and total) at different velocities in the three human locomotion techniques. The drag coefficients varied between 0.61 and 1.04, decreasing with velocity. It is possible to note that drag coefficient was prone to firstly drop (from 0.28 m/s to 2.5 m/s) and afterwards raised and kept reasonably constant (from 0.61 to 0.70). The pressure component varied between 0.38 and 0.52 and the viscous between 0.05 and 0.54. In the walking condition, the total drag coefficient ranged between 0.51 and 1.04, running between 0.65 and 0.68 and, sprinting from 0.61 to 0.64. Thus, overall the drag coefficients decreased with velocity.

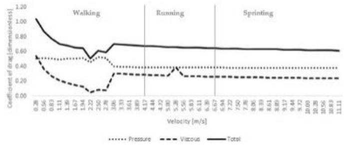


Figure 4. Pressure, viscous and total drag coefficient from 0.28 m/s to 11.11 m/s for the three locomotion techniques (walking: 0.28 – 4.17 m/s; running: 4.17 – 6.39 m/s; sprinting: 6.67 – 11.11 m/s).

Figure 5 depicts the drag variations at different velocities in the three types of locomotion analysed. As expected, drag increased with velocity.  The total drag varied between 0.50 and 34.97 N, The pressure drag component between 0.02 N and 21.47 N, and the viscous drag component between 0.02 and 13.50 N. The pressure drag presented a higher contribution in comparison to the viscous drag at the selected velocities for the three types of human locomotion.

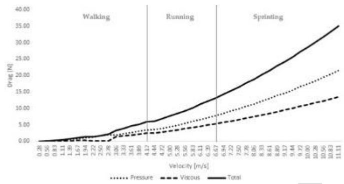


Figure 5. Pressure, viscous and total drag variations from 0.28 m/s to 11.11 m/s in the three locomotion techniques (walking: 0.28 – 4.17 m/s; running: 4.17 – 6.39 m/s; and sprinting: 6.67 – 11.11 m/s).

Regarding the possibility of walking or running at velocities between 2.22 m/s and 4.17 m/s. Comparing walking and running between 2.2 m/s and 4.17 m/s, walking presented higher pressure and total drag in comparison to running (Figure 6). Also, walking had lower viscous drag for speeds slower than 2.78 m/s; whereas, running showed lower viscous drag at velocities faster than 3.08 m/s. The differences between running and walking across different velocities ranged between 8% and 11% for pressure drag, 7% and 37% for viscous drag, and 2% and 11% for total drag.

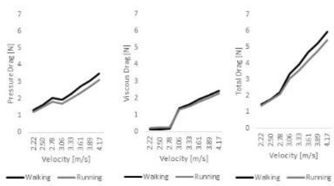

Figure 6. Pressure (left panel), viscous (middle panel) total drag (right panel) between 2.22 m/s and 4.17 m/s when walking and running.

The contribution of pressure drag to total drag varied between 50% and 90%, and in the case of viscous drag between 10% and 50% in the walking condition (Figure 7, top panel). In the running condition, pressure drag contribution ranged from 60% to 90% (Figure 7, middle panel). As far as sprinting is concerned, pressure drag contribution was about 60% (Figure 7, bottom panel). Thus, the viscous drag contributions were between 10% and 50% when walking, 10% and 40% running, and 40% sprinting. Therefore, the pressure drag was the components presenting the highest contribution to total drag.

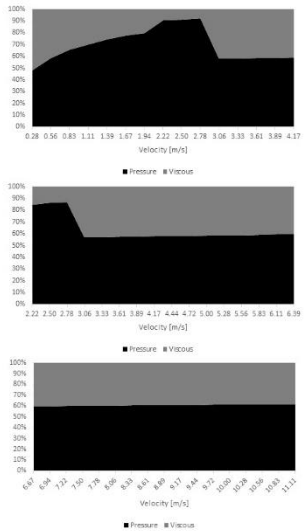


Figure 7. Contribution of pressure and viscous drag to total drag at the selected velocities for walking (top panel), running (middle panel) and sprinting (bottom panel).

*Walking and running comparisons*

Power models presented significant relation and very high effect sizes with velocity for walking ($R^2$ = 0.986; p< 0.001) and running ($R^2$ = 0.990; p< 0.001). The powerline for walking (Figure 7, top panel) and running (Figure 8, bottom panel) are presented in Figure 8.

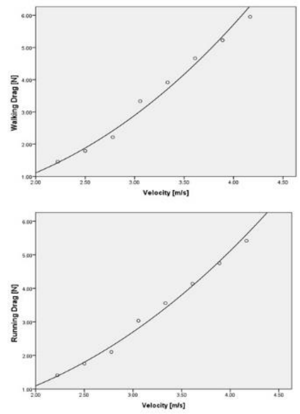


Figure 8. Trend lines (solid line) for drag variations and with velocity for walking (top panel) and running (bottom panel).

The drag variations equations for walking and running are presented in equations 4 and 5, respectively:

$$Y = 0.216 + x^{2.326} \quad (4)$$

$$Y = 0.235 + x^{2.223} \quad (5)$$

As noted in the equations, the walking locomotion type is prone to increase more in comparison to running; where, the exponent is 0.103 higher for walking. That is only observed for the range of velocities between 2.22 and 4.17 m/s; where, the drag presents a power increasing with velocity.

**Discussion**

The aim of this study was to assess the pressure, viscous and total drag that acts on an athlete at different velocities by locomotion type and that the walking demanded higher drag in comparison to running for the same velocities. It was hypothesized that the pressure drag differs from the viscous drag and the drag increases with velocity and that running present higher drag in comparison to walking.

The numerical simulations by CFD were used to assess the drag. This methodology has been used in different sports [16], [18] and athletics [4], [5], [32]. The wind tunnel is the gold standard method to assess aerodynamics [25]. However, the CFD allow to breakdown the drag into pressure and viscous drag [17]. This is the first study assessing athlete’s drag by CFD with a human body geometry created with 3D software’s. Most of the studies have scanned the participants [2], [7], [17], [18], [28]. This study can help to predict athlete's performance without the need to evaluate for data acquisition in real-time and face-to-face.

The coefficient of drag varied between 0.61 and 1.04 and mostly decreased with velocity. This is the first study reporting an athlete coefficient of drag variations by velocity and locomotion type (walking, running, and sprinting). The coefficient of drag variations was about 41%. We failed to find any study in running assessing coefficient of drag. However, in cycling it is possible to present Cd variations about 37% [21]. In a cylinder, the coefficient of drag is possible to vary about 69% [35]. That said, regarding the different geometries of the walking, running, and sprinting and in comparison, to cyclists and a cylinder, the variations of 41% are in agreement with literature. Additionally, for velocities between 2.22 m/s and 3.33 m/s the coefficient of drag varied (decreased, increased, decreased and increased) till reach a trend to diminish with velocity. This is possible to explain by the drag crisis phenomenon where is possible to note variations in coefficient of drag at different velocities [21].

The drag varied between 0.05 N and 5.95 N for walking and 1.41 N and 39.97 N for running. The pressure drag varied from 0.02 and 3.50 for walking and 1.19 N to 21.47 N for running. For the viscous drag, for walking varied between 0.02 N and 2.45 N and 0.21 N and 13.49 for running. The pressure drag had a higher contribution in comparison to viscous drag for the selected velocities. The drag for elite runners is about 0.5 N/Kg [1]. That said, considering the participant of the current study, for a participant with 78 Kg, the drag may be about 39 N. The results are in accordance with the current study. In another study [4], the authors presented a drag area for one runner of 0.272 $m^2$ at 5.88 m/s. Assuming this drag area for the current study settings, the drag estimation vary between 0.01 N and 21.69 N. However, for the same condition (5.88 m/s) the estimations are 6.08 N. In the present study, at 5.83 m/s the drag was 10.25 N. The results were slightly above the literature. That can be explained by: (i) the inter-individual differences between participants; (ii) different turbulence models; (iii) numerical simulations inputs (velocity and temperature).

The pressure drag contribution for total drag were between 50% and 90% across different speeds. The pressure drag contribution increased with speed. This is supported with literature in different sports. In wheelchair racing, the pressure drag contribution to total drag was about 55% [17]. Also in cycling [15], pressure drag contribution to total drag is higher than 75% at typical mean speed (11.11 m/s). To the authors' best knowledge, no study assessed total, pressure and viscous drag in running or walking athletes. However, the higher contribution of pressure drag was expected based on sports aerodynamics literature.

Finally, in the present study, the running condition presented lower drag in comparison to the walking condition. This was also supported by the power curve models, were the equation exponent was higher for walking. That is possible to explain by a more vertical position during the walking when comparison to running [12]. Moreover, the exponential values were in agreement with theoretical model where drag is dependent of the squared velocity ($F_d = 0.5\rho AC_dv^2$) and the power curves were 2.362 and 2.223 exponentials for walking and running [38]. However, less drag may result in runners lower energy cost and the literature reported that running is more economic than walking at specific speed [29].

Altogether, this is the first trial assessing walking and running aerodynamics by CFD. It was noted that, for the same range of velocities (2.22 m/s – 4.17 m/s) typically reached by athletes, the drag was higher for walking. The results of this study allow to support that, regarding aerodynamics, running is a more economic human locomotion in comparison to walking. Several studies in sports sciences [5], [28] focus more on drag analysis precisely because it is more useful for analysts, coaches and runners [5]. Since this work is more directed to sports scientists, information related to pressure maps, coefficients, streamlines are of higher importance to physics and mechanical engineering researcher [17], [18]. Based on our study, coaches may estimate more training variables such as power or energy cost [21]. That may also support the reason why running is considered a more economic locomotion in comparison to walking [29]. Upon that, long distance athletes may use running for sessions' volume (i.e., time) based trainings for lesser aerodynamic resistance. However, this study has some limitation: (i) only one participant of his competition level was recruited; (ii) only one environmental condition (temperature was tested); (iii) the mechanical loads were not estimated; (iv) the energy cost was not controlled. That said, this paper is specially an aerodynamics approach. Despite the criteria for the definition of the turbulence model, it is pertinent to emphasize that the results are in accordance with what could be expected from the literature [26], [35]. Additionally, as no wind tunnel comparisons were made, the parameters related to the numerical simulations may have different results with different turbulence models and different inputs to the numerical simulation [15], [16]. Saying also that it is necessary, perform comparisons between different turbulence models and in this study were not done [3], [21]. Moreover, this was the first analysis without the need for face-to-face real-time evaluations. Further studies are needed to clarify the turbulence model used or the size of the computational domain using numerical methodology in this gait analysis context.

## Conclusion

This study allowed to conclude that the drag increased with velocity for walking, running and sprinting. The walking presented for the selected range of velocities lower drag, followed by running and sprinting. Additionally, the pressure drag presented a higher contribution to total drag in comparison to the viscous drag. Regarding the comparison between walking and running, the running presented lower total, pressure and viscous drag in comparison to walking for the selected speeds. Finally, based on aerodynamics (total drag), it is possible to argue that, the running is a more economic human locomotion type in comparison to walking up to 11%. Drag analysis was a useful numerical simulation for analysts, coaches and runners.

## References


[1] BARBOSA TM, FORTE P, MARINHO DA, REIS VM. *Comparison of the world and European records in the 100m dash by a quasi-physical model*, Procedia Eng, 2016, 147:122–6.

[2] BARBOSA TM, MORAIS JE, FORTE P, NEIVA H, GARRIDO ND, MARINHO DA. *A comparison of experimental and analytical procedures to measure passive drag in human swimming*, PloS One, 2015, 10(7):e0130868.

[3] BARBOSA TM, RAMOS R, SILVA AJ, MARINHO DA. *Assessment of passive drag in swimming by numerical simulation and analytical procedure*, J Sports Sci, 2018, 36(5):492–8.

[4] BEAUMONT F, BOGARD F, MURER S, POLIDORI G, MADACI F, TAIAR R. *How does aerodynamics influence physiological responses in middle-distance running drafting*, Math Model Eng Probl, 2019, 6(1):129–35.

[5] BEAUMONT F, LEGRAND F, BOGARD F, MURER S, VERNEDE V, POLIDORI G. *Aerodynamic interaction between in-line runners: new insights on the drafting strategy in running*, Sports Biomech, 2021, 1–16. DOI:10.1080/14763141.2021.2006295.

[6] BEAUMONT F, TAIAR R, POLIDORI G, TRENCHARD H, GRAPPE F. *Aerodynamic study of time-trial helmets in cycling racing using CFD analysis*, J Biomech, 2018, 67:1–8.

[7] BLOCKEN B, DEFRAEYE T, KONINCKX E, CARMELIET J, HESPEL P. *CFD simulations of the aerodynamic drag of two drafting cyclists*, Comput Fluids, 2013, 71:435–45.

[8] BLOCKEN B. *Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations,* Build Environ, 2015, 91:219–45.

[9] BOHANNON RW, WILLIAMS ANDREWS A. *Normal walking speed: a descriptive meta-analysis*. Physiotherapy, 2011, 97(3):182–9.

[10] BRUGHELLI M, CRONIN J, CHAOUACHI A. *Effects of running velocity on running kinetics and kinematics.* J Strength Cond Res, 2011, 25(4):933–9.

[11] CAPPELLINI G, IVANENKO YP, POPPELE RE, LACQUANITI F. *Motor patterns in human walking and running,* J Neurophysiol, 2006, 95(6):3426–37.

[12] DEFRAEYE T, BLOCKEN B, KONINCKX E, HESPEL P, CARMELIET J. *Aerodynamic study of different cyclist positions: CFD analysis and full-scale wind-tunnel tests,* J Biomech, 2010, 43(7):1262–8.

[13] DINGENEN B, MALLIARAS P, JANSSEN T, CEYSSENS L, VANELDEREN R, BARTON CJ. *Two-dimensional video analysis can discriminate differences in running kinematics between recreational runners with and without running-related knee injury*, Phys Ther Sport, 2019, 38:184–91.

[14] DYER B. *The importance of aerodynamics for prosthetic limb design used by competitive cyclists with an amputation: An introduction*, Prosthet Orthot Int, 2015, 39(3):232–7.

[15] FORTE P, MARINHO DA, BARBOSA TM, MORAIS JE, FORTE P, MARINHO DA, *Analysis of a normal and aero helmet on an elite cyclist in the dropped position,* AIMS Biophys, 2020, 7(1):54–64.

[16] FORTE P, MARINHO DA, BARBOSA TM, MOROUÇO P, MORAIS JE. *Estimation of an elite road cyclist performance in different positions based on numerical simulations and analytical procedures*, Front Bioeng Biotechnol, 2020, 8: 538. DOI: 10.3389/fbioe.2020.00538.

[17] FORTE P, MARINHO DA, MORAIS JE, MOROUÇO PG, BARBOSA TM. *The variations on the aerodynamics of a world-ranked wheelchair sprinter in the key-moments of the stroke cycle: A numerical simulation analysis*, PLoS One, 2018, 13(2):e0193658.

[18] FORTE P, MARINHO DA, NIKOLAIDIS PT, KNECHTLE B, BARBOSA TM, MORAIS JE. *Analysis of cyclist's drag on the aero position using numerical simulations and analytical procedures: A case study*, Int J Environ Res Public Health, 2020, 17(10):3430.

[19] FORTE P, MARINHO DA, SILVEIRA R, BARBOSA TM, MORAIS JE. The *aerodynamics and energy cost assessment of an able-bodied cyclist and amputated models by computer fluid dynamics*, Medicina, 2020, 56(5):241.

[20] FORTE P, MORAIS JE, BARBOSA TM, MARINHO DA. *Assessment of able-bodied and amputee cyclists' aerodynamics by computational fluid dynamics*. Front Bioeng Biotechnol. 2021, 9:644566. DOI: 10.3389/fbioe.2021.644566.

[21] FORTE P, MORAIS JE, P. NEIVA H, BARBOSA TM, MARINHO DA. *The drag crisis phenomenon on an elite road cyclist—a preliminary numerical simulations analysis in the aero position at different speeds*, Int J Environ Res Public Health, 2020, 17(14):5003.

[22] FORTE, P., BARBOSA, T. M., & MARINHO, D. A. *Technologic appliance and performance concerns in wheelchair racing–helping Paralympic athletes to excel. New perspectives in fluid dynamics*. Chaoqun, L., Ed.; IntechOpen: Rijeka, Croatia, 2015, 101-121.

[23] FUKUCHI CA, FUKUCHI RK, DUARTE M. *Effects of walking speed on gait biomechanics in healthy participants: a systematic review and meta-analysis*, Syst Rev, 2019, 8(1):153.

[24] GARDAN N, SCHNEIDER A, POLIDORI G, TRENCHARD H, SEIGNEUR JM, BEAUMONT F, FOURCHET F, TAIARC R. *Numerical investigation of the early flight phase in ski-jumping*, J Biomech, 2017, 59:29–34.

[25] HIRATA K, OKAYAMA T, TERAOKA T, FUNAKI J. *Precise aerodynamics measurements of a track runner using a wind-tunnel moving-belt system, P*rocedia Eng, 2012;34:32–7.

[26] JONES AM, KIRBY BS, CLARK IE, RICE HM, FULKERSON E, WYLIE LJ, WILKERSON DP, VANHATALO A, WILKINS BW. *Physiological demands of running at 2-hour marathon race pace,* J Appl Physiol, 2021, 130(2):369–79.

[27] MANNION P, TOPARLAR Y, BLOCKEN B, HAJDUKIEWICZ M, ANDRIANNE T, CLIFFORD E. *Computational fluid dynamics analysis of hand-cycle aerodynamics with static wheels: Sensitivity analyses and impact of wheel selection,* Proc Inst Mech Eng, Part P: J Sports Eng Technol, 2021, 235(4):286–300.

[28] MARINHO DA, MANTHA VR, VILAS-BOAS JP, RAMOS RJ, MACHADO L, ROUBOA AI, Silva AJ. *Effect of wearing a swimsuit on hydrodynamic drag of swimmer, Braz Arch Biol Technol*, 2012, 55:851–6.

[29] MCNEILL ALEXANDER R. *Energetics and optimization of human walking and running: The 2000 Raymond Pearl memorial lecture*, Am J Hum Biol, 2002, 14(5):641–8.

[30] O'DONOGHUE P, GIRARD O, REID M. TENNIS. *Routeldge handbook of sports performance analysis*. London: Routledge, 2013:404–14.

[31] POGNI M, PETRONE N, ANTONELLO M, GOBBATO P. *Comparison of the aerodynamic performance of four racing bicycle wheels by means of CFD calculations*, Procedia Eng, 2015, 112:418–23.

[32] POLIDORI G, LEGRAND F, BOGARD F, MADACI F, BEAUMONT F. *Numerical investigation of the impact of Kenenisa Bekele's cooperative drafting strategy on its running power during the 2019 Berlin marathon*, J Biomech, 2020, 107:109854. DOI: 10.1016/j.jbiomech.2020.109854

[33] PUELLES MAGÁN G, TERRA W, SCIACCHITANO A. *Aerodynamics analysis of speed skating helmets: Investigation by CFD simulations*, Appl Sci, 2021, 11(7):3148.

[34] RASICA L, PORCELLI S, MINETTI AE, PAVEI G. *Biomechanical and metabolic aspects of backward (and forward) running on uphill gradients: another clue towards an almost inelastic rebound,* Eur J Appl Physiol, 2020, 120(11):2507–15.

[35] ROCA-DOLS A, LOSA-IGLESIAS ME, SÁNCHEZ-GÓMEZ R, BECERRO-DE-BENGOA-VALLEJO R, LÓPEZ-LÓPEZ D, RODRÍGUEZ-SANZ D, JIMÉNEZ EM, CALVO-LOBO C. *Effect of the cushioning running shoes in ground contact time of phases of gait,* J Mech Behav Biomed Mater, 2018, 88:196–200.

[36] ROOS PE, BUTTON K, VAN DEURSEN RWM. *Motor control strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: an observational study,* J NeuroEngineering Rehabil, 2014, 11(1):19.

[37] ROUBOA A, SILVA A, LEAL L, ROCHA J, ALVES F. *The effect of swimmer's hand/forearm acceleration on propulsive forces generation using computational fluid dynamics,* J Biomech, 2006, 39(7):1239–48.

[38] THORSTENSSON A, NILSSON J, CARLSON H, ZOMLEFER MR. *Trunk movements in human locomotion,* Acta Physiol Scand, 1984, 121(1):9–22.

[39] VAN DRUENEN T, BLOCKEN B. *Aerodynamic analysis of uphill drafting in cycling,* Sports Eng, 2021, 24(1):1–11.

[40] WUNDERSITZ DWT, GASTIN PB, RICHTER C, ROBERTSON SJ, NETTO KJ. *Validity of a trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running*, Eur J Sport Sci, 2015, 15(5):382–90.