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

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The drag in walking, running and sprinting locomotion can be assessed by analytical procedures and experimental techniques. However, assessing the drag variations by the above-mentioned types of locomotion 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.

Key words: *locomotion, CFD, drag, comparison, aerodynamics*

1. Introduction

Human locomotion is one of the main topics of research in biomechanics [13]. Higher ability to walk and run [11], and jump or squat 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 the fact 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 100 m 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 with walking at a given velocity

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[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 may allow for the explanation of the differences between human locomotion regarding economy and performance.

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

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

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

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 (Eq. (3)). Finally, Re (Eq. (4)) is dependent of the body length (L), fluid flow velocity (U), air density (ρ) and fluid dynamic viscosity (μ).

$$\mathbf{C}_d = \mathbf{f}(\mathbf{Re}), \quad (3)$$

$$\mathbf{Re} = \frac{\rho L U}{\mu}. \quad (4)$$

Based on Eqs. (1)–(4), the body positions 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 depend of the human locomotion type. Walking is performed at lower speeds than running and sprinting (being sprinting the fastest). Thus, it is expected for the drag to 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 allows for better understanding of 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 assessing an athlete's drag using numerical simulations was found [4]. However, the authors only reported the pressure maps and pressure coefficients at 5.88 m/s. No study assessing an athlete's drag at different speeds was found. On top of that, to the author's best knowledge, no study assessing pressure, viscous and total drag in walking condition was found.

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 sports [22], [27]. The CFD presented concordant data in comparison with analytical procedures and experimental testing [3], [18]. This method allows for the assessment of 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's body, as the less the fluid is dragged to the athlete, the less the viscous drag [3], [17]. This method has been used with scanned participants into 3D models as the above-mentioned studies. However, recent methods have created three dimensional geometries, representative of the real objects [18]. To the authors' best knowledge, this is 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 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.

2. Materials and 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 the Declaration of Helsinki. The scientific committee of the Douro Higher Institute of Educational Sciences approved this research.

3D model

A male human representative's 3D model was created using Blender (Blender 2.92, Blender Foundation, Amsterdam, Netherlands) based on the participant's anthropometrics. A static walking position (Fig. 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 (Fig. 1, middle panel) and sprinting (Fig. 1, right panel) models were created in Blender software (Blender Foundation 2.91.0, Amsterdam, Netherlands). The geometries were created in the mid-stance [3]. The walking participant's CAD model was re-converted and exported to object (*.obj*) in Geomagic Studio (2013, 3D System, Rock Hill, SC, USA). This procedure was conducted because the original file was edited and corrected, then the final CAD model was obtained. The blender software enabled us 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.

Fig. 1. Walking, running and sprinting participant's 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 (Fig. 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.

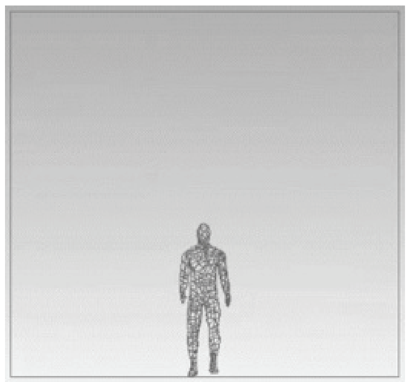

Fig. 2. Domain around the geometry of the walking participant

The surface area of the current computational domain has considered the CFD's criteria of the practice guidelines [8], [33] (Fig. 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's geometry was at 2.5 m from the inlet portion for each simulation.

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's 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 enabled us 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.

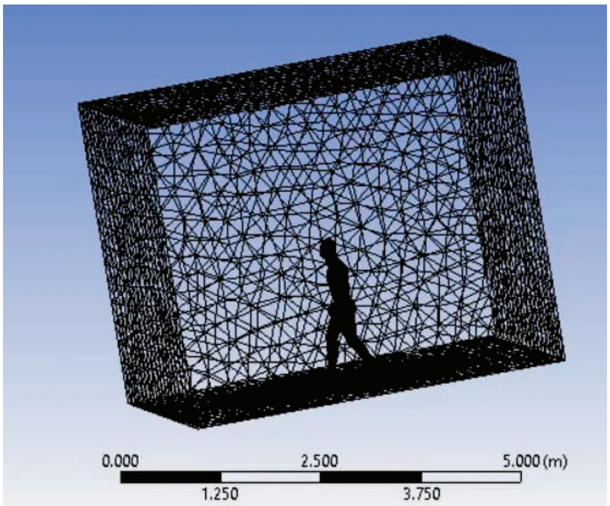

Fig. 3. Projected surface area of the participant's 3D model

Numerical simulations

The Ansys Fluent Module (Ansys Workbench 16.0, Ansys Inc., Pennsylvania, PA, US) enables us to solve the Reynolds-Average-Navier-Stokes equations. The Fluent CFD code, makes it possible 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-ε, realizable k-ε, RNG and RST. In the present study the realizable k-ε 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-ε turbulence model was proceeded using a RANS model based on previous studies on cycling [18], [21]. Moreover, the Realizable k-ε showed higher computation economy in comparison to Standard k-ε, RST and RNG k-ε 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 1×10^{-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:

$$C_{dp} = \frac{0.5 p A v^2}{F_{dp}}, \quad (7)$$

$$C_{dp} = \frac{0.5 p A v^2}{F_{dp}}. \quad (8)$$

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 was found (between 2.22 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 for $R^2 < 0.04$, weak – for $0.04 \le R^2 < 0.16$, moderate – for $0.16 \le R^2 < 0.49$, high – for $0.49 \le R^2 < 0.81$ and very high – for $0.81 \le R^2 < 1.0$ [27]. For all the tests, the statistical significance was set at 5%.

3. Results

In this chapter, the results 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 are presented, and the drag coefficients and drag force comparisons between walking and running are presented.

Drag coefficients and drag forces descriptive analyses

In Figure 4, the drag coefficients (pressure, viscous and total) at different velocities in the three human locomotion techniques are depicted. 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 to 2.5 m/s) and afterwards raised and kept reasonably constant (from 0.61 to 0.70 m/s). 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.

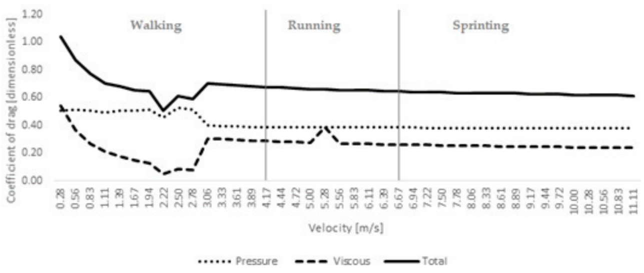

Fig. 4. Pressure, viscous and total drag coefficient from 0.28 m/s to 11.11 m/s for the three locomotion techniques (walking: 0.28–4.17 m/s; running: 4.17–6.39 m/s; sprinting: 6.67–11.11 m/s)

In Figure 5, the drag variations at different velocities in the three types of locomotion analysed are depicted. 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 with the viscous drag at the selected velocities for the three types of human locomotion.

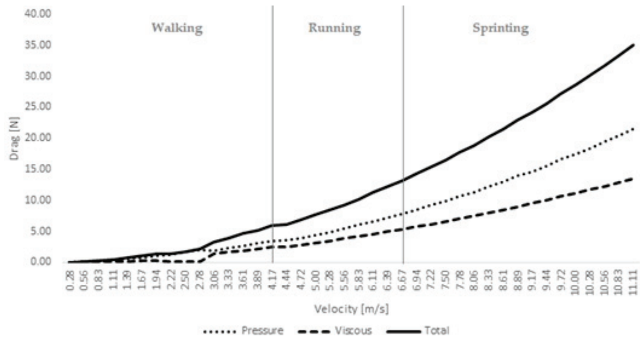

Fig. 5. Pressure, viscous and total drag variations from 0.28 m/s to 11.11 m/s in the three locomotion techniques (walking: 0.28–4.17 m/s; running: 4.17–6.39 m/s; and sprinting: 6.67–11.11 m/s)

Comparing walking and running between 2.2 m/s and 4.17 m/s, walking presented higher pressure and total drag in comparison with running (Fig. 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.

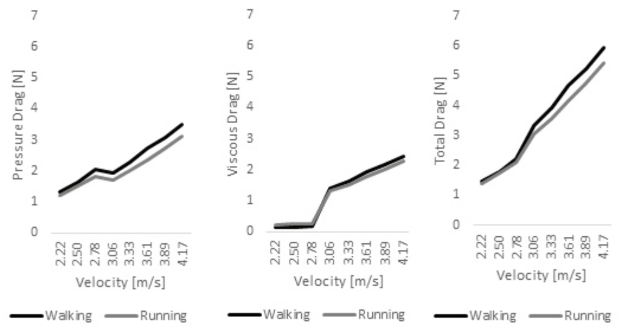

Fig. 6. Pressure (left panel), viscous (middle panel) total drag (right panel) between 2.22 m/s and 4.17 m/s when walking and running

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 (Fig. 7, top panel). In the running condition, pressure drag contribution ranged from 60 to 90% (Fig. 7, middle panel). As far as sprinting is concerned, pressure drag contribution was about 60% (Fig. 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.

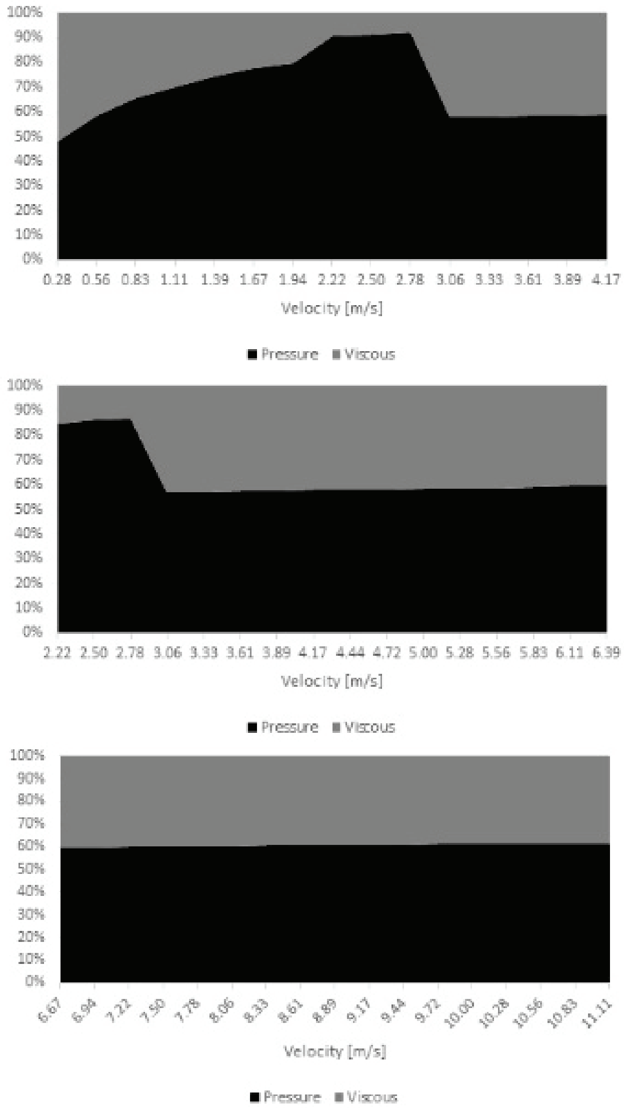

Fig. 7. Contribution of pressure and viscous drag to total drag at the selected velocities for walking (top panel), running (middle panel) and sprinting (bottom panel)

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 (Fig. 7, top panel) and running (Fig. 8, bottom panel) are presented in Fig. 8. The drag variations equations for walking and running are presented in Eqs. (9) and (10), respectively:

$$Y = 0.216 + x^{2.326}, \quad (9)$$

$$Y = 0.235 + x^{2.223}. \quad (10)$$

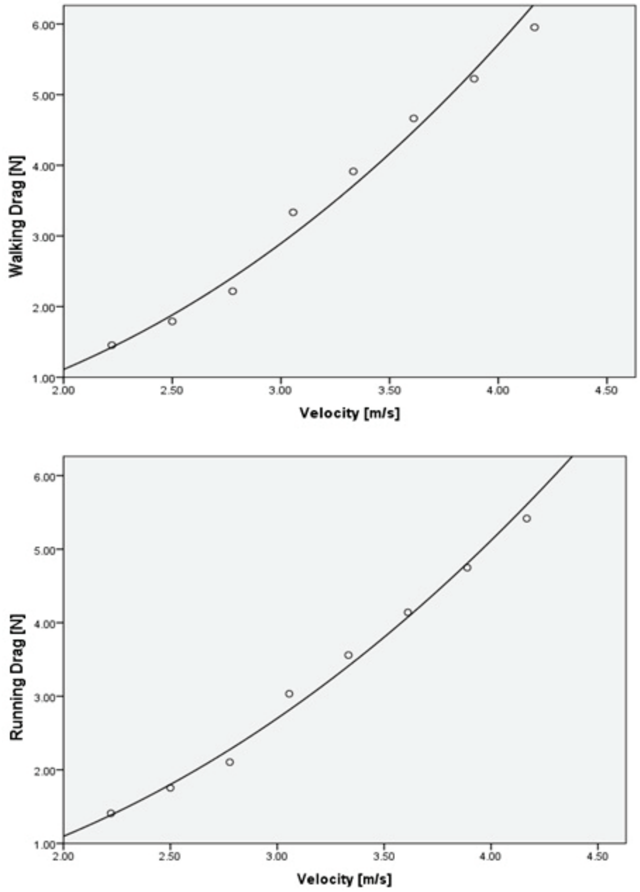

Fig. 8. Trend lines (solid line) for drag variations and with velocity for walking (top panel) and running (bottom panel)

As noted in the equations, the walking locomotion type is prone to increase more in comparison with running, where the exponent is by 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.

4. 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 with 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 with walking.

The numerical simulations by CFD were used to assess the drag. This method 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 allows to break down 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 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 C_d variations of 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 with 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 it is possible to note variations in coefficient of drag at different velocities [21].

The drag varied between 0.05 and 5.95 N for walking and 1.41 and 39.97 N for running. The pressure drag varied from 0.02 and 3.50 N for walking and 1.19 to 21.47 N for running. The viscous drag, varied between 0.02 and 2.45 N for walking and 0.21 and 13.49 for running. The pressure drag had a higher contribution in comparison with viscous drag for the selected velocities. The drag for elite runners was 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 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 was between 50 and 90% across different speeds. The pressure drag contribution increased with speed. This is accordance with literature on 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 with 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 ($F_d = 0.5\rho AC_d v^2$) 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 (2.22–4.17 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 with 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 has 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, performance 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 method in this gait analysis context.

5. Conclusions

This study made it possible 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 with the viscous drag. Regarding the comparison between walking and running, the running presented lower total, pressure and viscous drag in comparison with walking, for the selected speeds. Finally, based on aerodynamics (total drag), it is possible to argue that the running is more economic human locomotion type than walking by up to 11%. Drag analysis was a useful numerical simulation for analysts, coaches and runners.

Founding

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