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Raphael Mesquita[a], Patrick Willems[a], Valentina Natalucci[b], Francesco Luciano[b], Gaspare Pavei[b], Arthur Dewolf[a*]

a Lab. Biomechanics & Physiology of Locomotion, UCLouvain, Louvain-la-Neuve, Belgium
b Lab. Physiomechanics, Univ. Milan, Italy
* Corresponding author: arthur.dewolf@uclouvain.be

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1. Introduction

During terrestrial locomotion, to move across any environment, one must expend energy to overcome the drag (F_d) due to the airflow. Air resistance, at a certain velocity, is directly proportional to an object's projected frontal area (A) multiplied by the drag coefficient (C_d) and by the dynamic pressure of a moving air stream, q, ($F_d = q \times C_d \times A$) (Hoerner, 1965).

In still air, the speed of the relative airflow is equal to a subject's moving speed, which during human locomotion is generally low (<25km/h) equating to negligible drag (Pugh, 1971). Indeed, as the total mechanical work done by the body against drag is <10% of total mechanical work during walking and running, improving aerodynamics during locomotion does not lead to major performance improvements, contrary to other sports such as skating or cycling (di Prampero, 1986). However, when performance tends towards its limits, even small changes can lead to important time gains.

Experimental data of legged locomotion in a wind tunnel are scarce. Recently we investigated the effect of drag on the walking and running mechanics (Mesquita et al., 2024). F_d increases with square wind speed ($U2$) and, at wind speeds above 12 m/s, drag differs between walking and running due to a change in the drag area (C_dA) which decreases exponentially both with U and $U2$ (Pecchiari et al., 2023). Changes in C_dA can be due to changes in C_d, which is related to wind speed and airflow regime, or a change in A. The latter has been previously characterised by a cylinder in human locomotion (Pugh, 1971).

In our recent paper, we concluded that as F_d increases, to limit air resistance subjects adapt their C_dA (Mesquita et al., 2024), most likely by reducing their surface exposed to the drag. However, we did not dissociate between the two variables. The goal of the present study was firstly to compare our present findings to previous static measurements of projected frontal area (Davies, 1980; Pugh, 1971). Secondly, determine how the frontal area changes with increasing wind speeds and to what extent the decrease in C_dA is solely due to a change in A?

2. Methods

Based on a power analysis, eight male endurance athletes (age: 32±6 y, mass: 63.2±6.6 kg; height: 1.77±0.05 m, PB 10000 m: 31:20±01:12 min:s) walked and ran at 1.5 and 4 m/s respectively, on an instrumented treadmill in a wind tunnel. Wind speeds (U) ranged from -15 to 15 m/s, where the negative and positive signs indicate tailwind and headwind, respectively. U deviated from the nominal wind speed on average by 2 ± 0.4% over all trials. Informed written consent was obtained and the study followed the guidelines of the Declaration of Helsinki. All procedures were accepted by the local ethics committee (Politecnico di Milano, n°16/2022). Bilateral, full-body 3D kinematics were captured at 250 Hz with an 8-camera (6 MX-13 and 2 T20-S) VICON system (Oxford, UK) placed around the treadmill. Participants were equipped with 18 retro-reflective markers glued onto the skin. Data were oversampled at 1kHz and lowpass filtered (Bessel, cut-off frequency:

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30Hz). The frontal area was estimated using a polygon surface function (LABVIEW) from the instantaneous bilateral frontal plane coordinates of the Vth metatarsal, external malleolus, external femoral condyle, greater trochanter, shoulder, and temple markers and averaged per stride. The error in A by excluding the arms was expected to be offset by considering the lower limbs as a single block. To observe the difference in strategy between locomotion without wind and against wind, a ratio between the subject's frontal area over the subject's frontal area without added wind, A/A_o, was measured. Between 13–84 strides were analysed per condition, and for all subjects a total of 8850 strides were analysed (5443 in running, 3307 in walking). A mixed-effect model regressed the A and A/A_o over U and U^2 to assess which had the lowest Akaike Information Criterion. The fixed effect of wind (F) and significance (p-value, $\alpha = 0.05$) were reported. Differences between walking and running were assessed by pooling data together and analysing wind, speed, and the interaction effect for A/A_o.

3. Results and discussion

Frontal area decreases with increasing nominal wind speed in walking ($F = 1622.8$ $p < 0.001$) and running ($F = 1812.7$ $p < 0.001$). A/A_o decreases with stronger headwinds ($F = 20.1$ $p < 0.001$) and increases with increasing tailwinds, rising more in running than in walking ($F = 10.81$ $p < 0.001$).

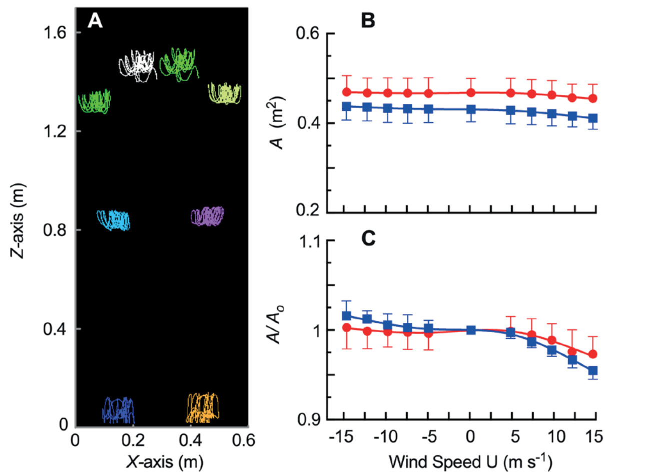

Figure 1. Panel A: Frontal area (A) model of one subject walking with a 15 m/s headwind. **Panel B:** A as a function of U in walking (red) and running (blue). **Panel C:** ratio A/A_o. Symbols represent the grand mean ± SD of all subjects. Lines are 3rd knot spline fits.

Frontal area has previously been calculated in standing by photographic measurements in studies with smaller sample sizes (Davies, 1980; Pugh, 1971). Here, based on kinematic data recorded over multiple strides, we obtain an average value of 0.139 x subject height^2 in locomotion without wind. This slightly lower value compared to Davies (1980) of 0.142 x subject height^2 can be partly explained by our subjects being in motion (Pugh, 1971).

Table 1. Average C_d and C_dA as a function of U in both head, (H) and tailwind (T) for walking (W) and running (R).

U (m/s)	Walk Run	Wind direction	C_d	C_dA (m²)
0	W/R	/	/	/
5	W	T	1.08±0.04	0.51±0.04
	R		1.11±0.04	0.48±0.03
	W	H	1.15±0.05	0.54±0.05
	R		1.07±0.06	0.46±0.05
7.5	W	T	1.01±0.04	0.48±0.04
	R		1.06±0.04	0.46±0.04
	W	H	1.08±0.04	0.50±0.05
	R		1.03±0.05	0.44±0.04
10	W	T	1.00±0.04	0.47±0.04
	R		1.05±0.04	0.45±0.03
	W	H	1.07±0.03	0.49±0.05
	R		1.00±0.04	0.42±0.03
12.5	W	T	1.00±0.04	0.47±0.04
	R		1.03±0.04	0.45±0.03
	W	H	1.07±0.04	0.49±0.03
	R		1.00±0.04	0.42±0.03
15	W	T	0.99±0.03	0.46±0.04
	R		1.01±0.04	0.44±0.03
	W	H	1.05±0.04	0.48±0.03
	R		0.99±0.04	0.41±0.03

A is slightly larger in walking than in running, likely due the double stance phase and more erect posture in walking. As headwind increases, subjects tuck their head in and tilt forwards to reduce their frontal area exposed to drag (Davies, 1980, Mesquita et al., 2024). Against tailwinds, particularly in running, subjects slightly increase frontal area, mostly done by leaning backwards into the wind. This gives the wind a larger projected area to exert force on, decreasing the power done during running propulsion (Mesquita et al., 2024). Contrarily, C_dA decreases against tailwinds despite an increase in A (Mesquita et al., 2024). This indicates a decrease in C_d, possibly due to changes in the airflow regime which tends towards turbulence beyond the speeds studied presently (Davies, 1980; Pugh, 1971).

4. Conclusion

Our study confirms and updates the relationship of frontal area and body height which is constantly used in computational fluid dynamics (CFD) simulations (Fernandes et al., 2023). This investigation is particularly relevant in the field of sports science where the marathon world record approaches the 2-hour mark.

Conflict of interest

The authors have no conflict of interests to report.

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