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HOW DO SMALL HORIZONTAL IMPEDING FORCES AFFECT PHYSIOMECHANICS OF RUNNING?

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Coorientador: Prof. Dr. Wouter Hoogkamer

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Dedicated to *Black Science Community*

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RESUMO

Introdução: Os benefícios da estratégia de *drafting* no desempenho de maratonistas de elite são conhecidos. Porém, devido a diferentes métodos para converter as forças de arrasto na corrida em potência metabólica e as altas forças horizontais impeditivas (HIF) utilizadas nos estudos anteriores, não está claro como os fatores fisiomecânicos são afetados nessas condições. **Objetivo:** Quantificar como pequenas HIF afetam a fisiomecânica de corredores de longa distância. **Métodos:** Doze corredores homens (idade: 26,1 ± 3,5 anos, massa corporal: 66,5 ± 5,6 kg, estatura: 1,79 ± 0,09 m) participaram do estudo. O estudo consistiu em três sessões de coletas de dados. Em cada sessão, os sujeitos correram em duas vezes uma velocidade (12 ou 14 ou 16 $km.h^{-1}$) nas três forças (0, 4 e 8 N) totalizando 6 tentativas de 5 minutos por sessão, com 5 minutos de recuperação entre as tentativas. Nós mensuramos o consumo de oxigênio submáximo e forças de reação do solo, simultaneamente. As forças de reação do solo foram duplamente integradas para cálculo das variáveis do sistema massa mola, e as assimetrias contato-despregue e *rebound* no software Labview. A potência metabólica, eficiência aparente (E_{ff}), impulsos de frenagem (I_{brake}) e de propulsão (I_{prop}), picos de força de frenagem ($F_{brake,peak}$) e propulsão ($F_{prop,peak}$), tempo de contato (t_c) e aéreo (t_a), comprimento do passo (L), *duty factor*, tempo de contato efetivo (t_{ce}) e aéreo efetivo (t_{ae}), tempo de propulsão (t_{push}) e frenagem (t_{brake}), deslocamento vertical do centro de massa (s_v): durante o contato (s_c), fase aérea (s_a), contato efetivo descendente ($s_{ce,down}$), contato efetivo ascendente ($s_{ce,up}$), aéreo efetivo descendente ($s_{ae,down}$) e aéreo efetivo ascendente ($s_{ae,up}$), frequência de passo (f_{step}), frequência natural do sistema (f_{syst}), rigidez vertical (k_{vert}), força vertical (F_v), velocidade vertical do centro de massa durante a fase descendente ($v_{v,max,down}$) e ascendente ($v_{v,max,up}$), armazenamento de energia elástica (EL) e as assimetrias t_{ce}/t_{ae}, t_{push}/t_{brake}, $s_{ae,down}/s_{ae,up}$, $s_{ce,down}/s_{ce,up}$ e $v_{v,max,down}/v_{v,max,up}$ foram calculadas. Foi utilizada uma ANOVA de duas vias para medidas repetidas com post-hoc de Bonferroni para a comparação entre as variáveis ($\alpha = 0,05$). **Resultados:** A potência metabólica aumentou 6,13% por 1% do peso corporal de HIF. Com o aumento das HIF, I_{brake} reduziram, enquanto I_{prop} aumentaram. O L e F_v reduziram com aumento das HIF correspondente a 8 N. As variáveis t_c, t_a, $t_{ce,}$ t_{ae}, *duty factor*, $F_{brake,peak,}$ $F_{prop,peak,}$ s_a, f_{step}, f_{syst}, k_{vert}, EL e assimetria entre t_{ce}/t_{ae} foram todas independentes das HIF. A assimetria entre $v_{v,max,down}/v_{v,max,up}$ reduziu quando 4 e 8 N de HIF foi aplicada, enquanto 8 N tornou as relações entre $s_{ae,down}/s_{ae,up}$ e $s_{ce,down}/s_{ce,up}$ simétricas. Não houve qualquer efeito da velocidade de corrida e das HIF na E_{FF}, s_v, s_c, e na assimetria entre t_{push}/t_{brake}. **Conclusão:** Concluímos que o sistema massa-mola pode ser otimizado com altas HIF. Essa otimização acontece quando as altas HIF (8 N) tornam as relações entre $s_{ae,down}/s_{ae,up}$, $s_{ce,down}/s_{ce,up}$ e $v_{v,max,down}/v_{v,max,up}$ simétricas. Entretanto, custo energético para superar I_{prop} contra HIF aumenta a potência metabólica em 6,13% por 1% da massa corporal de HIF.

Palavras-chave: *drafting*; economia de corrida; desempenho; modelo massa-mola, mecânica.

ABSTRACT

Background: Benefits of drafting strategies for elite marathon performance are known. However, due to different methods to convert aerodynamic drag force to metabolic power and high horizontal impeding forces (HIF) implemented in previous studies, it is unclear how physiomechanical is affected at these conditions. **Objective:** We aimed to quantify how small HIF affect the physiomechanics of long-distance runners. **Methods:** Twelve male runners (age: 26.1 ± 3.5 years, mass: 66.5 ± 5.6 kg, height 1.79 ± 0.09 m) participated. The study consisted of three data collection sessions. On each session, the subjects ran one velocity two times per session (12, 14 and 16 km.h^{-1}) at three HIF (0, 4 and 8 N) in a total of six 5-minute trials with 5 minutes recovery in-between. We measured submaximal oxygen uptake and ground reaction forces simultaneously. Ground reaction forces were double integrated for calculating spring-mass model variables, landing take-off and rebound asymmetries on Labview software. The metabolic power, apparent efficiency (E_{ff}), braking (I_{brake}) and propulsive impulses (I_{prop}), peak of braking ($F_{brake,peak}$) and propulsive forces ($F_{prop,peak}$), contact (t_c) and aerial time (t_a), step length (L), duty factor, effective contact (t_{ce}) and aerial time (t_{ae}), push (t_{push}) and brake duration (t_{brake}), vertical displacement of the center of mass (s_v) during contact time (s_c), aerial time (s_a), effective contact downward ($s_{ce,down}$), effective contact upward ($s_{ce,up}$), effective aerial downward ($s_{ae,down}$) and effective aerial upward ($s_{ae,up}$), step frequency (f_{step}), natural frequency of the system ($f_{syst.}$), vertical stiffness (k_{vert}), vertical force (F_v), vertical velocity of the center of mass downward ($v_{v,max,down}$) and upward ($v_{v,max,up}$), elastic energy storage (EL) and t_{ce}/t_{ae}, t_{push}/t_{brake}, $s_{ae,down}/s_{ae,up}$, $s_{ce,down}/s_{ce,up}$ and $v_{v,max,down}/v_{v,max,up}$ asymmetries were calculated. We performed a two-way ANOVA with repeated measures and Bonferroni post-hoc for comparing the variables ($\alpha = 0.05$). **Results:** The metabolic power increased by 6.13% per 1% body weight of HIF. With increasing HIF, I_{brake} decreased while I_{prop} increased. The L and F_v reduced with increase of HIF corresponding of 8 N. The variables t_c, t_a, $t_{ce,}$ t_{ae}, duty factor, $F_{brake,peak,}$ $F_{prop,peak,}$ s_a, f_{step}, $f_{syst.}$, k_{vert}, EL and t_{ce}/t_{ae} asymmetry were all independent of HIF. t_{brake}, $v_{v,max,down}$, $v_{v,max,up}$ and elastic energy storage were all independent of HIF. The asymmetry between $v_{v,max,down}/v_{v,max,up}$ reduced when was applied 4 and 8 N of HIF, whereas 8 N becomes $s_{ae,down}/s_{ae,up}$ and $s_{ce,down}/s_{ce,up}$ symmetrical. The E_{ff}, s_v, s_c, and t_{push}/t_{brake} asymmetry were not affected by running velocity and HIF. **Conclusion:** We concluded that spring-mass model can be optimized at high HIF. This optimization is related to symmetrical relationship between $s_{ae,down}/s_{ae,up}$, $s_{ce,down}/s_{ce,up}$ e $v_{v,max,down}/v_{v,max,up}$ with high HIF (8 N). Therefore, although attenuated by elastic mechanism, the metabolic power increases 6.13% by adding HIF of 1% body weight.

Keywords: drafting; running economy; performance; spring-mass model; mechanics.

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ABBREVIATIONS

$a_{v,max}$	Maximal vertical Acceleration
BCoM	Body center of mass
BW	Body weight
C	Cost of transport
E_{ff}	Apparent mechanical efficiency
EL	Elastic energy storage
eff_{musc}	Muscle efficiency
HIF	Horizontal impeding force
$F_{brake,peak}$	Peak of braking forces
$F_{prop,peak}$	Peak of propulsive forces
f_{syst}	Natural frequency of the system
f_{step}	Step frequency
F_v	Vertical force
I_{brake}	Braking impulses
I_{prop}	Propulsive impulses
k_{vert}	Mass-specific stiffness
L	Step length
s_a	Vertical displacement of BCoM during aerial time
s_{ae}	Vertical displacement of BCoM during effective aerial time
$s_{ae,down}$	Vertical displacement of BCoM during effective aerial downward phase
s_c	Vertical displacement of BCoM during contact time
s_{ce}	Vertical displacement of BCoM during effective contact time
$s_{ce,up}$	Vertical displacement of BCoM during effective aerial upward phase
$s_{ae,down}/s_{ae,up}$	Asymmetry between vertical displacement of BCoM during effective during effective aerial downward and upward phases
$s_{ce,down}/s_{ce,up}$	Asymmetry between vertical displacement of BCoM during effective during effective contact downward and upward phases
s_v	Vertical displacement of BCoM vertical displacement of BCoM
t_a	Aerial time

t_{ae}	Effective aerial time
t_{brake}	Brake duration
t_{c}	Contact time
t_{ce}	Effective contact time
$t_{\mathrm{ce}}/t_{\mathrm{ae}}$	Asymmetry between effective contact and aerial time
t_{push}	Push duration
$t_{\mathrm{push}}/t_{\mathrm{brake}}$	Asymmetry between push and brake duration
$v_{\mathrm{v,max,down}}$	Vertical velocity of BCoM downward
$v_{\mathrm{v,max,up}}$	Vertical velocity of BCoM upward
$v_{\mathrm{v,max,down}}/v_{\mathrm{v,max,up}}$	Asymmetry between vertical velocity of BCoM downward and upward

SUMMARY

CHAPTER 1

GENERAL INTRODUCTION

This chapter contains four sections: general presentation, problem statement, aims of dissertation and finally a literature review.

1.1 General presentation

1.1.1 Contextualization and delimitation of the study

This work is part of research line from the LOCOMOTION research group (Mechanics and Energetics of Terrestrial Locomotion/UFRGS, Brazil) under coordination from my advisor, Prof. Leonardo Alexandre Peyré-Tartaruga. The group's primary goals are to study the basic energy-saving mechanisms (elastic and pendulum-like) of human locomotion in different gaits, task conditions, environments, and population. This Master's Degree dissertation is the outcome of a partnership between the LOCOMOTION group of Escola de Educação Física, Fisioterapia e Dança (ESEFID) at Universidade Federal do Rio Grande do Sul (UFRGS), my co-advisor, Prof. Wouter Hoogkamer (University of Massachusetts), and Prof. Rodger Kram from Integrative Physiology Department at University of Colorado Boulder.

This partnership started back in 2017 when Prof. Wouter collaborated in one of my studies, entitled: "Gait functionality of individuals with visual impairment who participate in sports", as part of my graduation in Physical Education at UFRGS. It was reinforced in 2018 when I was invited to a 2-month vising scholar program at University of Colorado, Boulder in USA, when I had the opportunity to improve my research skills in biomechanics and physiology. At that time, we started working on a project to quantify the effects to air resistive forces on running economy and running performance, using a horizontal impeding force method. Project was written and data were collected during those 2 months and when I came back to Brazil, we discussed the contents and theoretical approach with Prof. Leonardo, which was important to improve our conceptual model, including the elastic storage analysis from a physiomechanics point of view, emerging from this my Master thesis.

Prof. Wouter and Dr. Rodger have been leading a series of studies investigating marathon performance aspects such as running economy, running shoes, and drafting strategies during running. Prof. Leonardo has solid studies in the field of physiomechanics such as running economy and elastic storage in elderly populations and long-distance runners. Here we join forces with the aim to understand how small horizontal impeding forces (comparable to air resistive forces) affect physiomechanics of running.

1.1.2 Structure of dissertation

This study was developed at Integrative Physiology Department of University of Colorado Boulder and at Exercise Research Laboratory of ESEFID. This dissertation is divided into five chapters.

The first chapter provides a general introduction, the aims of dissertation and literature review.

The second chapter presents a randomized crossover study of the metabolic cost of overcoming air resistive forces in distance running in competitive male runners.

The third chapter presents a randomized crossover study of the effect of small horizontal impeding force on spring-mass model and asymmetries of bouncing step in long-distance runners.

The fourth chapter presents a summarized the results from the two studies on integrative point of view and general conclusion of dissertation.

The fifth chapter lists the abstracts and papers published during master´s degree period.

1.2 Problem statement

The energy cost to overcome air resistance forces during locomotion for long distances and high velocities have been discussed over the years. In the nature, birds overcome drag forces and support their body weight migrating non-stopping more than 1,000 km (SCHMIDT-NIELSEN, 1972). To save energy during the travel birds adopt optimal formation, such “v” formation, conferring to them aerodynamic advantage and reducing their energy expenditure in 14% in comparison to flying solo (WEIMERSKIRCH et al., 2001). On cycling, it is common to use of drafting strategies to reduce the drag forces. An athlete can reduce his drag force in 27.1 % cycling shielded 1 m by other leader cyclist (BLOCKEN et al., 2013) and there is a decrease in oxygen consumption of 27% when a cyclist was shielded in line formation at 40 km.h^{-1} (MCCOLE et al., 1985). In running the drag forces cannot be neglected. The air resistive forces represent 7.5 to 8% of total energy cost of running (PUGH, 1970; 1971), and 6.5% of the oxygen consumption can be reduced if a runner stay 1 m behind to other at 16.2 km.h^{-1} (PUGH, 1971).

A known difference between indoor and overground running is the lack of air resistive forces during a treadmill. Jones and Doust (1996) suggested the uphill running of +1% should counterbalance the difference in metabolic power between outdoor and treadmill in running velocity above 12 km.h^{-1}. Other authors suggested that there are little or null differences between two conditions in oxygen consumption in running velocities up to 17 km.h^{-1} (MCMIKEN and DANIELS, 1976; BASSETT et al., 1985). However, according to Pugh (1970) and Pugh (1971), it is expected that the difference in metabolic power between outdoor and treadmill running depends directly on running velocity.

Pugh (1971) and Davies (1980) studied the energy cost of running to overcoming air resistive forces using a wind tunnel. Due to difficult experimental design, they tested a small number of runners and they did not systematically assess the effects of running speed and drag force. Alternatively, Lloyd and Zacks (1972), Zacks (1973) and later Chang and Kram (1999) quantified the energy cost of overcoming resistive forces applying horizontal impeding forces to the waist to simulate the effect of the air resistive forces. The abovementioned studies were performed at relatively low running speeds (~ 12 km.h^{-1}), and with heavy horizontal impeding forces (3 to 6% of runners' body weight). Chang and Kram (1999) data suggest that the metabolic power increases approximately 4% for every 1% of body mass at 12 km.h^{-1}. It has been shown that drag forces for elite runners with dimensions of Eliud Kipchoge and Kenenisa Bekele are around at 6.6 N at 21.1 km.h^{-1} and 7.7 N at 20.7 km.h^{-1} (POLIDORI et al., 2020; BEVES and FERGUSON, 2017) representing air resistive forces of 1.29 and 1.4% of their body weight, respectively. Futures studies should apply resistive forces more representative to real conditions.

The metabolic power to overcome air resistive forces, drafting strategies and time saving for elite marathon runners have been estimated (BEVES and FERGUSON, 2017; HOOGKAMER, SNYDER and ARELLANO, 2018; HOOGKAMER, SNYDER and ARELLANO, 2019; POLIDORI et al., 2020). However, each study used a different method for converting aerodynamic force to the metabolic cost of running and, hence, running performance. Is not clear how metabolic power respond to increase of air resistance forces and running velocities.

Chang and Kram (1999) using horizontal impeding forces found that metabolic cost increases linearly with horizontal impeding forces (0 to 6% per percentage of body weight of applied force) at 12 km.h^{-1}. Davies (1980) using wind tunnel also found a linear relationship between metabolic cost and wind velocities from 5 to 15 m.s^{-1} at running velocities up to 21.6 km.h^{-1}. However, Pugh (1971) using wind tunnel found at 13.5 km.h^{-1} the relationship between oxygen consumption and all wind velocities applied (up to 18.5 m.s^{-1}) was linear, while at 16.1 km.h^{-1} was curvilinear at wind velocities over 12.5 m.s^{-1}. In addition, comparing running overground in calm air and treadmill, Pugh (1970) found a curvilinear relation between the increase in extra oxygen intake and running velocity at overground conditions (when running and wind velocities are equal).

During running against air resistive forces on treadmill that runners leaned their trunk forward and some cases they changed their technique from rearfoot to forefoot strike (DAVIES, 1980; PUGH, 1971). During steady state, level treadmill running braking and propulsive impulses must be equal and opposite (GOTTSCHALL and KRAM, 2005). It was demonstrated that with increment of horizontal impeding forces (0 to 6% of body weight) the oxygen consumption increased 30.2% and propulsive impulses increased while braking impulses decreased (CHANG and KRAM, 1999). Therefore, it seems that runners apply a greater amount of propulsive forces when they are running against drag forces and these forces are energetically costly due to muscular work and respective muscular efficiency employed (ALEXANDER, 1976).

The mass-spring model is the mechanism that explain the minimization of energy expenditure during running (BLICKHAN, 1989; MCMAHON and CHENG, 1990). It considers the runner body as a mass and the leg as a spring. In this model, the mass oscillates symmetrically at a frequency on a spring with specific stiffness during step storing and releasing elastic energy (BLICKHAN, 1989; MCMAHON and CHENG, 1990). The elastic energy is stored in the tendon-muscle units during negative work phase (t_{brake}) when the center of mass falling and is released in positive work (t_{push}), when the center of mass is raising (CAVAGNA, SAIBENE and MARGARIA, 1964). Additionally, the capacity of energy storage is associated with the amount of force applied during effective contact time (t_{ce}), when vertical force is greater than body weight, and how longer effective aerial time (t_{ae}) is to use the stored energy, when the vertical force is lower than body weight (CAVAGNA et al., 1988). Cavagna et al. (2006) showed that human running presented deviation from this symmetrical ideal model due the force-velocity muscle relationship. The $t_{\mathrm{push}} > t_{\mathrm{brake}}$ in low and intermediate running velocities are asymmetrical and becomes symmetrical ($t_{\mathrm{push}} = t_{\mathrm{brake}}$) at high velocities, whereas $t_{\mathrm{ae}} = t_{\mathrm{ce}}$ at low and intermediate running velocities and becomes asymmetrical in high running velocities ($t_{\mathrm{ae}} > t_{\mathrm{ce}}$). Therefore, optimal bouncing elastic is enhanced when $t_{\mathrm{push}} = t_{\mathrm{brake}}$ and $t_{\mathrm{ae}} > t_{\mathrm{ce}}$ (CAVAGNA, 2009). Other running asymmetries related to vertical velocity and displacement of the center of mass during t_{ae} and t_{ce} are discussed in detail in Cavagna’s study (CAVAGNA, 2006).

Mesquita et al. (2020) quantified the effect of high horizontal impeding forces (5, 10 and 15% of body weight) on running mechanical variables at running velocities from 8 to 16 km.h^{-1}. The authors found that the increment of horizontal impeding forces impair the elastic bouncing ($t_{\mathrm{ae}} = t_{\mathrm{ce}}$ and $t_{\mathrm{push}} > t_{\mathrm{brake}}$) at high running velocities. These findings are in line with Dewolf, Peñailillo and Willems (2016) that compared mechanical variables during overground and uphill running and found that with increase of incline the elastic bouncing $t_{\mathrm{ae}} = t_{\mathrm{ce}}$ and $t_{\mathrm{push}} > t_{\mathrm{brake}}$. However, paradoxically Mesquita et al. (2020), found that highest load evaluated (15% of body weight) increased the recovery of external mechanical work in 16% at 8 km.h^{-1} (the lowest running velocity). This recovery was reduced at high velocities.

Based on previous studies, the metabolic cost of running with horizontal impeding forces increases according the propulsive impulses (CHANG and KRAM, 1999), though the energy transduction between potential and kinetic energies is improved (MESQUITA et al., 2020). A deep analysis of metabolic power to overcome horizontal impeding forces comparable to air resistive forces in large sample of competitive runners and at higher running velocities could improve the understanding of the energy cost of running overground, running economy and the accuracy of drafting and time savings calculations. Additionally, the spring-mass model variables such landing-takeoff ($t_{\mathrm{push}}/t_{\mathrm{brake}}$) and rebound ($t_{\mathrm{ae}}/t_{\mathrm{ce}}$) can demonstrate if running against small resistive forces becomes the system resonant or dissonant and therefore saving energy.

1.3 Aims

1.3.1 General aim

The purpose of this dissertation was to quantify how small horizontal impeding forces affect the running physiomechanics variables across a range of running velocities.

1.3.2 Specific aims

1) Quantify how small horizontal impeding forces (0, 4 and 8 N) affect metabolic power in a large sample of competitive runners over a range of velocities (12, 14 and 16 km.h^{-1}).

2) Quantify how small horizontal impeding forces (0, 4 and 8 N) can save energy by spring-mass model through asymmetries of bouncing step (rebound and landing take-off) in long-distance runners.

1.3.3 Hypothesis

1) We expect that with increase of small horizontal impeding forces (0, 4, and 8 N) across running velocities (12, 14, 16 km.h^{-1}) the metabolic power will increase linearly.

2) We expect that with increase of horizontal impeding forces the landing-takeoff (t_{push}/t_{brake}) and rebound (t_{ae}/t_{ce}) will not be changed, however, another asymmetry of spring-mass model: vertical velocity of the center of mass during downward and upward ($v_{v,max,down}/v_{v,max,up}$) will become symmetrical due to altered values during fatigue conditions found in previous work (FISCHER, 2010).

1.4 Literature review

1.4.1 Aerodynamic drag forces during running

Aerodynamic drag forces during locomotion are an inevitable phenomenon and the concerns regarding its effects at different running velocities through different measurements have been described (HILL, 1928; SHANEBROOK and JASZCZAK, 1976). The main factors associated to drag forces during running are running velocity, body dimensions (surface and frontal area), density of the air, wind velocity and wind direction such as tailwind, headwind, or crosswind (HILL, 1928; SHANEBROOK and JASZCZAK, 1976).

The drag forces (F) in N during running can be calculated using a standard equation proposed by Lord Rayleigh (1876), with information of projected frontal area (A_f) expressed in m^2, coefficient of drag (C_d), air density (ρ) in kg/m^3 and the running velocity (v) in $m.s^{-1}$:

$$F = 0.5\ A_f\ C_d\ \rho\ v^2 \qquad \text{Equation 1}$$

The A_f is related to general position adopted by runner during race (see Figure 1). It has been suggested that A_f during running is equal to 26% of surface area (PUGH, 1970; DU BOIS and DU BOIS, 1916) or 0.15 times the square of runner height (HILL, 1928). The C_d is ratio of F to a dynamic pressure (kinetic energy per unit volume of a moving solid body) of a moving air stream (PUGH, 1971). The C_d is a function of Reynold's number (*R*) that are dependent of kinematic viscosity of the air (air viscosity / ρ) and wind velocity on A_f (PUGH, 1971). It is expected a C_d around 0.8 - 0.9 during running (PUGH, 1971; HILL, 1928), whereas, for ρ, a value of 1.204 kg/m^3 is common in sea level at 20°C (KYLE and CAIOZZO, 1986), but it is worth noting that ρ decreases with increase of room temperature (PUGH, 1971).

Hill (1928) measured air resistive forces using small wind tunnel and a scaled physical model of a runner (0.2 m tall). In this runner, it was assumed two running body position: standing and running position (as shown in Figure 1). To determine the projected area, Hill used photography method and therefore he found 0.28 m^2 for standing position and lower values of 0.24 m^2 for running position. Further, the "*resistance*" called by Hill was measured using the following equations for both conditions, which F varies as the square of running velocity:

$$F = 0.45\ \rho\ v^2\ A_r\ (\text{running position}) \qquad \text{Equation 2}$$

$$\mathrm{F} = 0.49\ \rho\ \mathrm{v}^2\ \mathrm{A_s}\ \text{(standing position)} \qquad \text{Equation 3}$$

Where A_r is the projected area in running position (ft^2), A_s is the projected area in standing position (ft^2), v is the running velocity (feet per second), and ρ was 0.00237 and represents the air density at 15° C and at normal barometric pressure (expressed in lbs. per cubic foot divided to gravity to convert F in lbs. weight). To represent F during running in practical terms, Hill converted all units of Equation 2 and 3, running velocity in $m.s^{-1}$, the area in m^2 and F in kilograms:

$$\mathrm{R} = 0.056\ \mathrm{v}^2\ \mathrm{A_r}\ \text{(running position)} \qquad \text{Equation 4}$$

$$\mathrm{R} = 0.061\ \mathrm{v}^2\mathrm{A_s}\ \text{(standing position)} \qquad \text{Equation 5}$$

It was found the projected area during running could be represented by the square of height (H) in the proportion of 0.146 ($A_r = 0.146\ H^2$) in running position and 0.171 in standing position ($A_s = 0.171\ H^2$). Hill (1928) calculated the projected area for a 1.75 m of height and found $A_r = 0.446\ m^2$ in running position and $A_r = 0.520\ m^2$. Therefore, he corrected this proportion using a photograph of runner finishing a race and found a proportion of A_r equal to 0.15 H^2. Finally, it was concluded that A_r for a runner is approximately 0.464 m^2 and F is 0.0053 v^2 (lbs), where v is expressed in feet per second. For a runner during sprint of 38 $km.h^{-1}$ in a calm air (without wind), the Hill equation described above the F is 28 N and for running at 26 $km.h^{-1}$ the F is 13.3 N.

Another critical outcome in Hill (1928) was the effect of F on running performance. In a hypothetical scenario without air resistance a runner at 38 $km.h^{-1}$ could increase his maximal velocity by 5%. The increase of 5% in maximal running velocity would be possible in a real scenario with a tailwind velocity (when the wind is blowing in the same direction of a moving object) equal to 16.1 or 38.6 $km.h^{-1}$ improving his time in 3 and 5 s at 100 yards (~ 91 m), respectively. It is needed to highlight that F varies square of running velocity and, thus, when the same runner overcomes a headwind velocity (when the wind is blowing against the direction of a moving object) of 16.1 $km.h^{-1}$, his performance decreases in 5 s at the same distance.

Almost 50 years later, Shanebrook and Jaszczak (1976) improved the estimates of F in runners creating a segmented model during contact time. In this runner model, lower limbs, upper limbs, and trunk were considered cylinders and for the head was considered a sphere. Additionally, it was assumed a runner posture similar during race, where one arm and one leg on opposite sides of the trunk are bent forward and backward, respectively, as shown in Figure 1.

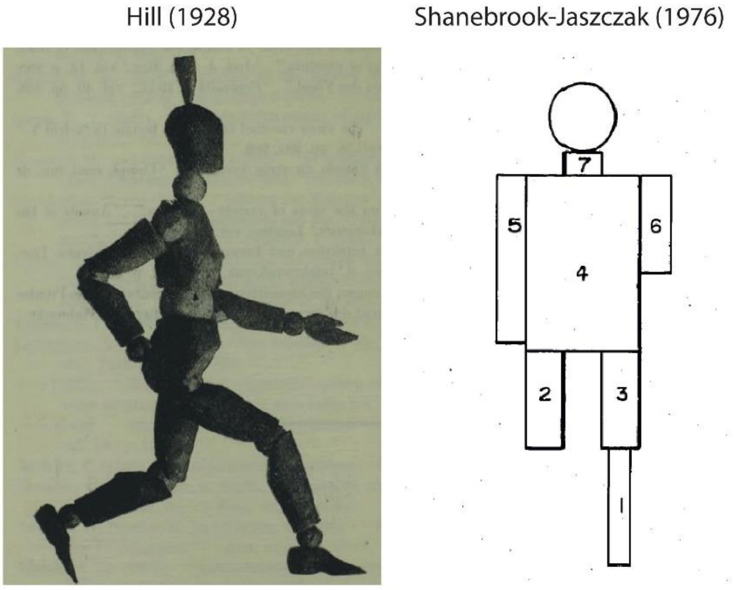

Figure 1. Drag Forces Models

Applying the Shanebrook and Jaszczak (1976) model to an American male adult (percentile 50 in body dimensions) sprinting at 36.2 $km.h^{-1}$ for 100 yards (91 m) with C_d 1.14, the authors found F of 30 N. It was also possible to observe that F varies when body dimensions changes. American male with percentile 2.5 at the same conditions F was 24.7 N ($C_d = 1.14$), while and with percentile 97.5 the F increased to 36.3 N. The findings of Shanebrook and Jaszczak (1976) model for a male percentile 50 are in line with Hill (1928) model for sprinter runners who found F of 28 N running at 38 $km.h^{-1}$. Future studies calculating F during long distance runners would elucidate energetics responses and time saving through drafting strategies (when a runner benefit from a low-pressure zone behind another leader runner) (HOOGKAMER, KRAM and ARELLANO, 2017).

Hoogkamer, Kram and Arellano (2017) calculated the F to Dennis Kimetto (1.71 m and 58 kg; $A_f = 0.450$ m^2) to overcome the 2-hr marathon pace. They used the Rayleigh's equation for F with C_d of 1.0, ρ equal 1.2 kg/m^3 and running velocity of 5.86 $m.s^{-1}$. Kimetto would face 9.2 N during the 2-hr marathon. However, the authors suggested that if there was cooperative drafting in which four elite marathoners in line (1 m of distance) alternating the leadership for 3 min (5 times for each one), the second half of marathon of the would be reached in 58:24 min. An interaction during this cooperative drafting with three runners also alternating for 3 min would allow the second half of marathon in 58:51, and 59:30 with only two runners cooperating. An updated model of cooperative drafting proposed by Hoogkamer, Snyder and Arellano (2019) with current world record marathonist Eliud Kipchoge (2:01:39), suggested that interaction of 3 Kipchoge-like runners is needed to break 2-hr marathon saving 1:51 min.

Currently, with technological advances, simulations using the Computational Fluid Dynamic (CFD) method also allow the calculation of F during running at different running posture, with or without additional wind velocities, high running velocities, different air conditions and temperatures. Beves and Ferguson (2017) using CFD method, simulated the effect of F on Eliud Kipchoge performance (2:00:25) at 21.1 km.h^{-1} during an unofficial marathon in Monza (Italy) in 2017. It was simulated 4 scenarios: 1°) Kipchoge running alone; 2°) the car in front of Kipchoge; 3°) Kipchoge drafting in delta formation; and 4°) the car in front of Kipchoge drafting in delta formation (see Figure 2). It was found 6.6 N for running alone at baseline. The F decreased from 6.6 to 4.6 N on the second scenario, decreased from 6.6 to 1.8 N when Kipchoge ran with delta formation and his F decreased from 6.6 to 1.25 N when Kipchoge ran with a car plus delta formation. They also suggested that 4:09 min was saved by delta formation in comparison to running alone.

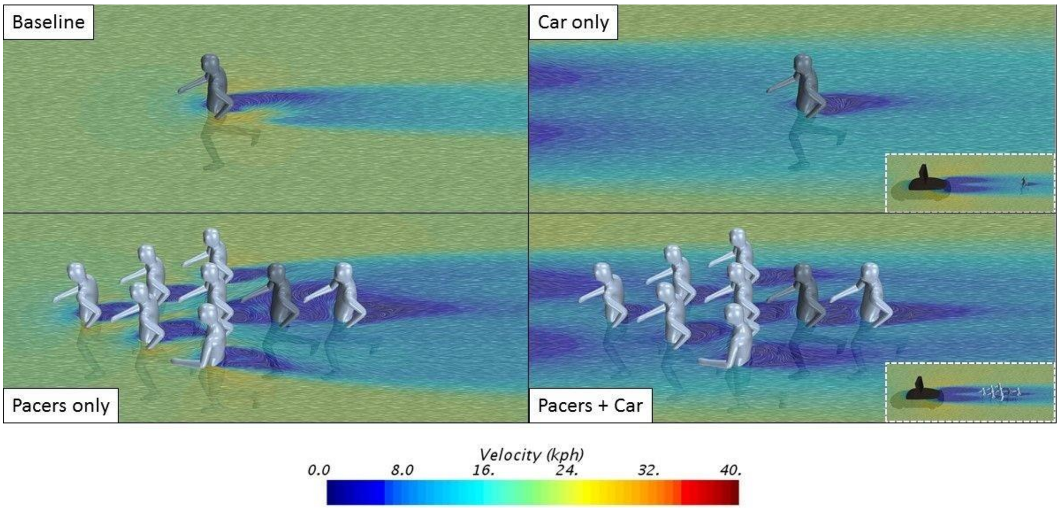

Figure 2. CFD simulation for Eliud Kipchoge (from Beves and Ferguson, 2017).

Polidori et al. (2020) simulated the F using CFD in various cooperative drafting configurations for Kenenisa Bekele (A_f = 0.475 m²) at 20.7 km.h^{-1}. The 3 pacers designed were positioned side by side (0.3 m) shielding Bekele (at 1.3 m). The authors found that when Bekele was running alone, the F was 7.77 N, while running between two pacers, it was 4.78 N. In another scenario, when Bekele ran behind a lateral pacer, the F was 3.47 N. Finally, when Bekele ran in optimal drafting (behind the middle pacer), the F was 3.32 N. Therefore, maximal drafting benefits it is not achieved only when a runner stay behind another runner.

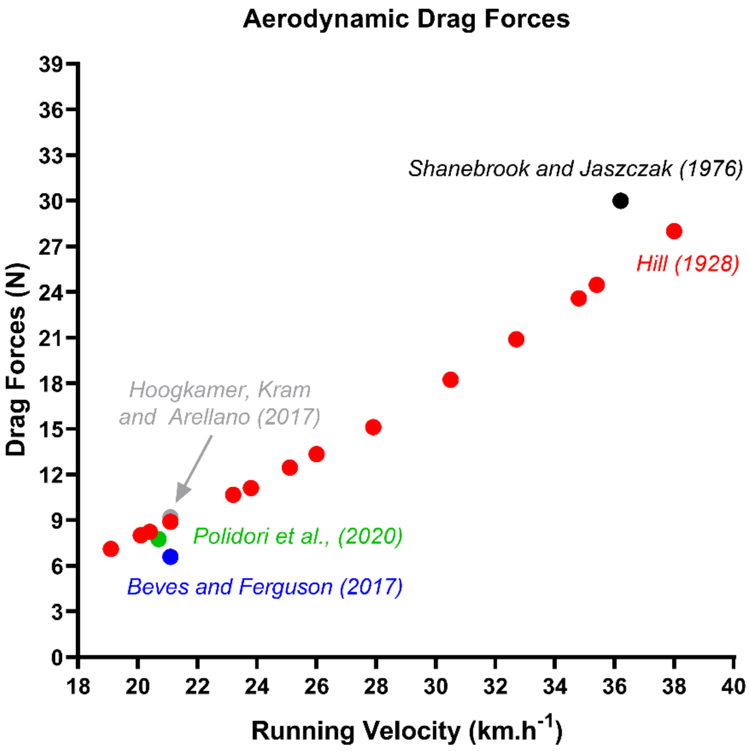

Figure 3. Drag forces across running velocities. It was extracted drag forces values during running from 5 studies: Hill (1928), in red circles for 1 runner with A_f = 0.464 m² at running velocities between 19.1 to 38 km.h^{-1}; Shanebrook and Jaszczak (1976) in black circle for 1 runner (A_f was not reported) at 36.2 km.h^{-1}; Beves and Ferguson (2017) in blue circle for Eliud Kipchoge (A_f was not reported) at 21.1 km.h^{-1}; Hoogkamer, Kram and Arellano (2017) in grey circle for Dennis Kimetto with A_f = 0.450 m² at 21.1 km.h^{-1}, and Polidori et al. (2020) in green circle for Kenenisa Bekele with A_f = 0.475 m² at 20.7 km.h^{-1}.

Based on previous studies (Figure 3), it possible to assume an elite marathon with dimensions of Kipchoge at 2-hr marathon (21.1 km.h^{-1}) would have the F around 6.6 to 9.9 N. Given the differences in methods for F calculation (equations and CFD simulations) and body dimensions reported, new F estimates at 2-hr marathon pace are needed to improve accurate time saving during running.

1.4.2 Effects of air resistive force on physiomechanics of running

There are four approaches to quantify the air resistive forces during running experimentally. The first direct methods are the use of wind tunnel on treadmill and add wind velocities at the same as the treadmill belt compared to running on treadmill with wind tunnel off (PUGH, 1971; DAVIES, 1980). The second compares running on treadmill and running outside the lab (overground) (PUGH, 1970; MCMIKEN and DANIELS, 1976; BASSETT et al., 1985; JONES and DOUST, 1996). The third is comparison between running overground and equivalent uphill running on treadmill (JONES and DOUST, 1996). Finally, the last one is horizontal impeding forces applied on waist belt like air resistive forces (LLOYD and ZACKS, 1972; ZACKS, 1973; CHANG and KRAM, 1999; MESQUITA et al., 2020). Here, we will describe the main findings related to methods cited on physiology and biomechanics outcomes.

In a seminal study, Pugh (1971) measured the energetics of long-distance running on a treadmill against wind tunnel effects. Pugh studied only one elite runner (A_f 0.478 m^2) at constant running velocities of 13.5 and 16.1 $km.h^{-1}$ at adjustable wind velocities of up to 18.5 $m.s^{-1}$. The oxygen consumption (VO_2) at 16.1 $km.h^{-1}$ increased from 3.05 $L.min^{-1}$ at baseline wind velocity to 4.96 $L.min^{-1}$ at 18.5 $m.\ s^{-1}$ of wind velocity. In addition, at 13.5 $km.h^{-1}$ the relationship between VO_2 and all wind velocities applied was linear, while at 16.1 $km.h^{-1}$ was curvilinear at wind velocities over 12.5 $m.s^{-1}$. Interestingly, the author reported that the runner changed his running technique from rearfoot to forefoot strike and leaned the trunk forward with an increase of running and wind velocities.

Another result of Pugh (1971) was the metabolic cost of drafting during running. The metabolic rate was reduced by 0.250 $L.min^{-1}$ at 6.0 $m.s^{-1}$ of wind velocity when the runner was shielded by another runner 1 m behind him at running velocity of 16.2 $km.h^{-1}$. Applying these results outside the lab in calm air, when running velocity equal to wind velocity, the VO_2 can be reduced by 6.5% with drafting. A total of 7.5% of energy was needed to overcome air resistive forces at 21.6 $km.h^{-1}$ and 13.6% for sprinting 100 m in 10 s using Pugh (1970) energy cost estimates.

Davies (1980) also quantified air resistive forces on VO_2 during running using a wind tunnel. Two trained and one male recreational runner ran on a treadmill at different running velocities against wind velocities from 1.5 to 18.5 $m.s^{-1}$. He found the energy cost to overcome air resistance on a calm day was 7.8% at 36 km.h^{-1}, 4% at 21.6 km.h^{-1} and 2% at 18 km.h^{-1}. Davies also reported changes in running technique with an increase of wind velocities. The recreational runner flexed his upper body forward with low wind velocities and slightly decreased his A_f from 0.430 m² (wind velocities 1 to 15 m.s^{-1}) to 0.425 m² (wind velocities > 15 m.s^{-1}). In contrast, both two trained runners radically adopted the same body position of recreational, however, they also presented a forefoot strike technique resulting in a significant decrease in A_f from 0.466 m² (wind velocities 1 to 15 m.s^{-1}) to 0.425 m² (wind velocities > 15 m.s^{-1}).

Pugh (1970) evaluated the VO_2 of seven runners on treadmill and overground at velocities up to 21.6 km.h^{-1}. An increase of 9.2% in VO_2 was found when they ran in another environment (treadmill to overground) with high values on overground trails. A side results crucial for understanding the effect of air resistive forces on VO_2 in Pugh (1970) study was the cubic relationship between the increase in extra oxygen intake (ΔVO_2) and running velocity at overground conditions (when running and wind velocities are equal). Therefore, an equation to estimate the increase in metabolic power at overground running was developed ($\Delta VO_2 = 0.00354\ A_f\ v^3$), where ΔVO_2 is expressed in L.min^{-1}, A_f in m² and v is the running velocity m.s^{-1}. Finally, it was estimated that 8% and 16% of total energy cost is due to overcome the air resistance at 21.5 and 36 km.h^{-1}, respectively.

Regarding studies comparing running on treadmill and overground, there are no or little effects on physiological variables at low running velocities. Considering the running velocity increases the F in square proportion (HILL, 1928), it is not a surprise studies that evaluated VO_2 requirements during treadmill and overground on a calm day and at low running velocities (i.e., up to 17 km.h^{-1}) do not found substantial differences (MCMIKEN and DANIELS, 1976; BASSETT et al., 1985). Contrary to findings described above, Jones and Doust (1996) found differences in VO_2 between treadmill and overground in velocities from 13.5 to 16.5 km.h^{-1}. In addition, contrary to Pugh (1970), the relationship between treadmill and overground was linear (r = 0.99), and an interesting correspondence between +1% on treadmill and running overground at running velocities of 10.5 to 18 km.h^{-1} was reported.

An alternative method to quantify the effect of air resistive forces on energy expenditure and biomechanics outcomes is the use of horizontal impeding forces (Figure 4). The external impeding loads in horizontal direction are applied when the aim is to know the headwind effects, while external aiding loads can be applied when the researcher aims to know the tailwind responses. These horizontal impeding forces are applied in the center of mass direction using rubber tubing connected to a pulley system to reduce the oscillation (LLOYD and ZACKS, 1972; ZACKS, 1973).

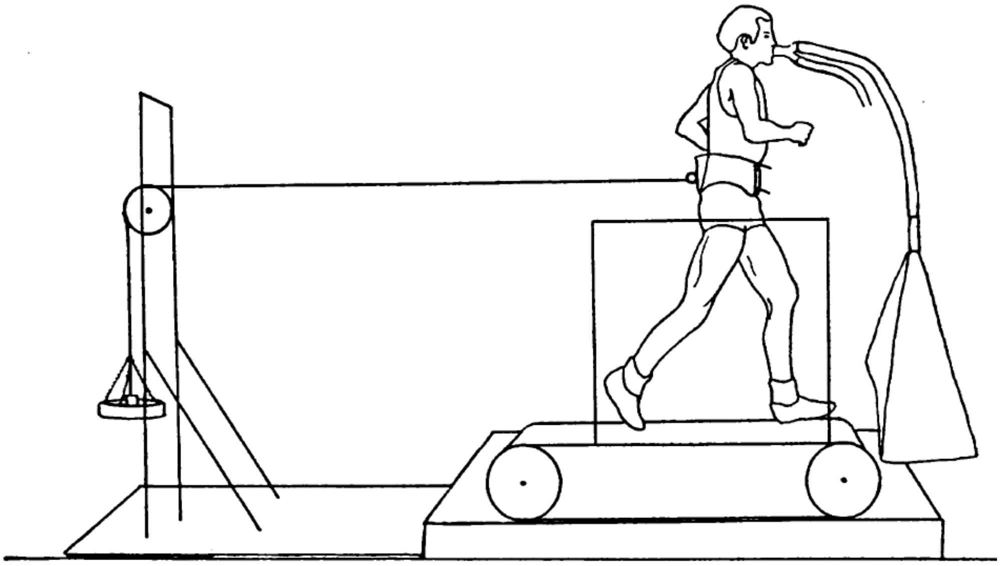

Figure 4. Horizontal impeding forces method (Lloyd and Zacks, 1972).

The study by Lloyd and Zacks (1972) was the first to assess the relationship between horizontal resistive forces and running energy expenditure. Three well-trained runners ran at 13 km.h^{-1} against horizontal impeding forces ranging between 12.2 and 53.9 N (2.2 and 9.6% of body weight, respectively). A linear relationship was found between the VO$_2$ and external loads at running velocities evaluated. These linear relationship results between VO$_2$ and horizontal impeding forces are in line with Zacks (1973) that applied horizontal impeding forces of 9.8 and 15.7 N (1.5 and 2.4% of their BW, respectively) in 4 runners. The apparent efficiency that represents the change in external mechanical power from unloaded running divided by the change in metabolic power from unloaded running was 36.1% (LLOYD and ZACKS, 1972) and 39.1% (ZACKS, 1973) without substantial differences between running velocities.

Years later, Chang and Kram (1999) investigated the effects of horizontal impeding forces during running and the mechanisms associated with energy expenditure. Eight well-trained reactional runners participated in metabolic and biomechanics experiments at 12 km.h^{-1} against 3 and 6% of BW. They found a linear relationship between VO$_2$, running velocity and all horizontal impeding forces evaluated. There was a significant increase of 30.2% in VO_2 with 6% BW of load in compared to the baseline condition. The propulsive impulses increased (47.5%), whereas braking impulses decreases (51.1%) without substantial differences in stride kinematics. It was suggested by the authors that generate propulsive forces are more metabolic expensive than braking forces.

In some cases, runners leaned the trunk forward and changed their technique from rearfoot to forefoot strike with increase at high wind velocities (PUGH, 1971; DAVIES, 1980), but only one study evaluated mechanical alteration for running at these conditions (MESQUITA et al., 2020). High horizontal impeding forces (up to 5, 10 and 15% of BW) modify the duration of positive (t_{push}) and negative work (t_{brake}) done to move BCoM forward (see Table 2), asymmetries of bouncing step and energies transduction (MESQUITA et al., 2020). More details of Mesquita et al. (2020) findings are discussed in section 1.4.3.

We summarized physiological and biomechanical responses of horizontal external loads, i.e., wind tunnel stimulus, treadmill versus overground, and horizontal impeding forces method are summarized in Table 1 and 2.

Table 1. Physiological responses of horizontal external loads

Study	**Velocities**	**Conditions**	**Variables**	**Results**	**Difference**
Pugh (1971)	16.0 $km.h^{-1}$	Baseline	VO_2 ($L.min^{-1}$)	3.05	O
	16.0 $km.h^{-1}$	Wind 18.5 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	4.96	↑
Davies (1980)	12.9 $km.h^{-1}$	Baseline	VO_2 ($L.min^{-1}$)	2.58	O
	12.9 $km.h^{-1}$	Wind 5.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	2.61	↑
	12.9 $km.h^{-1}$	Wind 8.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	2.95	↑
	12.9 $km.h^{-1}$	Wind 10.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	3.26	↑
	12.9 $km.h^{-1}$	Wind 12.5 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	3.68	↑
	12.9 $km.h^{-1}$	Wind 15.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	4.07	↑
	12.9 $km.h^{-1}$	Wind 18.1 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	4.45	↑
	14.5 $km.h^{-1}$	Baseline	VO_2 ($L.min^{-1}$)	3.08	O
	14.5 $km.h^{-1}$	Wind 5.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	3.18	↑
	14.5 $km.h^{-1}$	Wind 8.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	3.43	↑
	14.5 $km.h^{-1}$	Wind 10.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	3.78	↑
	14.5 $km.h^{-1}$	Wind 12.5 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	4.23	↑
	14.5 $km.h^{-1}$	Wind 15.0 $m.s^{-1}$	VO_2 ($L.min^{-1}$)	4.60	↑
Pugh (1970)	21.5 $km.h^{-1}$	Treadmill	VO_2 ($ml.kg^{-1}.min^{-1}$)	68.3	O
	21.5 $km.h^{-1}$	Overground	VO_2 ($ml.kg^{-1}.min^{-1}$)	74.6	↑
Bassett et al. (1985)	8.4 $km.h^{-1}$	Treadmill	VO_2 ($ml.kg^{-1}.min^{-1}$)	32.4	O
	8.4 $km.h^{-1}$	Overground	VO_2 ($ml.kg^{-1}.min^{-1}$)	33.3	=
	16.8 $km.h^{-1}$	Treadmill	VO_2 ($ml.kg^{-1}.min^{-1}$)	60.2	O
	16.8 $km.h^{-1}$	Overground	VO_2 ($ml.kg^{-1}.min^{-1}$)	59.5	=

Jones and Doust (1996)	10.5 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	29.6	O
	10.5 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	31.1	=
	12.0 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	34.6	O
	12.0 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	35.7	=
	13.5 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	39.0	O
	13.5 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	41.7	↑
	15.0 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	44.9	O
	15.0 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	48.1	↑
	16.5 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	51.0	O
	16.5 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	54.8	↑
	18.0 km.h^{-1}	Treadmill	VO$_2$ (ml.kg^{-1}.min^{-1})	57.3	O
	18.0 km.h^{-1}	Overground	VO$_2$ (ml.kg^{-1}.min^{-1})	60.5	=
	10.5 km.h^{-1}	Treadmill	HR (beats min^{-1})	116	O
	10.5 km.h^{-1}	Overground	HR (beats min^{-1})	119	=
	12.0 km.h^{-1}	Treadmill	HR (beats min^{-1})	124	O
	12.0 km.h^{-1}	Overground	HR (beats min^{-1})	128	=
	13.5 km.h^{-1}	Treadmill	HR (beats min^{-1})	137	O
	13.5 km.h^{-1}	Overground	HR (beats min^{-1})	140	=
	15.0 km.h^{-1}	Treadmill	HR (beats min^{-1})	149	O
	15.0 km.h^{-1}	Overground	HR (beats min^{-1})	153	=
	16.5 km.h^{-1}	Treadmill	HR (beats min^{-1})	160	O
	16.5 km.h^{-1}	Overground	HR (beats min^{-1})	165	=
	18.0 km.h^{-1}	Treadmill	HR (beats min^{-1})	171	O
	18.0 km.h^{-1}	Overground	HR (beats min^{-1})	174	=
Lloyd and Zacks (1972)	12.6 km.h^{-1}	Baseline	VO$_2$ (L.min^{-1})	3.20	O
	12.6 km.h^{-1}	53.9 N (HIF)	VO$_2$ (L.min^{-1})	3.96	↑
Chang and Kram (1999)	12.0 km.h^{-1}	Baseline	VO$_2$ (ml.kg^{-1}.min^{-1})	35.7	O
	12.0 km.h^{-1}	3 % BW	VO$_2$ (ml.kg^{-1}.min^{-1})	39.7	=
	12.0 km.h^{-1}	6 % BW	VO$_2$ (ml.kg^{-1}.min^{-1})	45.7	↑

Body weight (BW); Oxygen consumption (VO$_2$); Heart rate (HR); Horizontal impeding forces (HIF); Symbol (O) is related to baseline, (↑) significant increase in comparison to baseline, (↓) significant decrease in comparison to baseline, and (=) no differences in comparison to baseline. Chang and Kram (1999) used HIF method.

Table 2. Biomechanical responses of horizontal external loads

Study	Velocities	Conditions	Variables	Results	Difference
Chang and Kram (1999)	12.0 km.h^{-1}	Baseline	f_{stride} (Hz)	1.40	O
	12.0 km.h^{-1}	3 % BW	f_{stride} (Hz)	1.45	=
	12.0 km.h^{-1}	6 % BW	f_{stride} (Hz)	1.46	=
	12.0 km.h^{-1}	Baseline	t_c (s)	0.263	O
	12.0 km.h^{-1}	3 % BW	t_c (s)	0.269	↑
	12.0 km.h^{-1}	6 % BW	t_c (s)	0.268	↑
	12.0 km.h^{-1}	Baseline	Duty Factor	0.37	O
	12.0 km.h^{-1}	3 % BW	Duty Factor	0.39	=
	12.0 km.h^{-1}	6 % BW	Duty Factor	0.39	=
	12.0 km.h^{-1}	Baseline	I_{brake} (N/s)	13.9	O
	12.0 km.h^{-1}	3 % BW	I_{brake} (N/s)	10.1	↓
	12.0 km.h^{-1}	6 % BW	I_{brake} (N/s)	6.8	↓
	12.0 km.h^{-1}	Baseline	I_{prop} (N/s)	14.1	O
	12.0 km.h^{-1}	3 % BW	I_{prop} (N/s)	16.9	↑
	12.0 km.h^{-1}	6 % BW	I_{prop} (N/s)	20.8	↑
	12.0 km.h^{-1}	Baseline	Peak F_{brake} (N)	227.2	O
	12.0 km.h^{-1}	3 % BW	Peak F_{brake} (N)	189.3	↓
	12.0 km.h^{-1}	6 % BW	Peak F_{brake} (N)	147.4	↓

	12.0 km.h^{-1}	Baseline	Peak F_{prop} (N)	193.3	O
	12.0 km.h^{-1}	3 % BW	Peak F_{prop} (N)	210.9	↑
	12.0 km.h^{-1}	6 % BW	Peak F_{prop} (N)	238.0	↑
	12.0 km.h^{-1}	Baseline	F_v (N)	1670	O
	12.0 km.h^{-1}	3 % BW	F_v (N)	1583	=
	12.0 km.h^{-1}	6 % BW	F_v (N)	1574	=
	12.0 km.h^{-1}	3 % BW	E_{ff} (%)	62.6	O
	12.0 km.h^{-1}	6 % BW	E_{ff} (%)	54.5	↓
Mesquita et al. (2020)	8.0 km.h^{-1}	Baseline	t_c (s)	0.291	O
	8.0 km.h^{-1}	5% BW	t_c (s)	0.296	=
	8.0 km.h^{-1}	10% BW	t_c (s)	0.301	=
	8.0 km.h^{-1}	15% BW	t_c (s)	0.302	=
	10.0 km.h^{-1}	Baseline	t_c (s)	0.271	O
	10.0 km.h^{-1}	5% BW	t_c (s)	0.271	=
	10.0 km.h^{-1}	10% BW	t_c (s)	0.271	=
	10.0 km.h^{-1}	15% BW	t_c (s)	0.276	=
	12.0 km.h^{-1}	Baseline	t_c (s)	0.247	O
	12.0 km.h^{-1}	5% BW	t_c (s)	0.247	=
	12.0 km.h^{-1}	10% BW	t_c (s)	0.243	=
	12.0 km.h^{-1}	15% BW	t_c (s)	0.246	=
	14.0 km.h^{-1}	Baseline	t_c (s)	0.230	O
	14.0 km.h^{-1}	5% BW	t_c (s)	0.230	=
	14.0 km.h^{-1}	10% BW	t_c (s)	0.224	=
	14.0 km.h^{-1}	15% BW	t_c (s)	0.221	=
	16.0 km.h^{-1}	Baseline	t_c (s)	0.209	O
	16.0 km.h^{-1}	5% BW	t_c (s)	0.209	=
	16.0 km.h^{-1}	10% BW	t_c (s)	0.204	=
	16.0 km.h^{-1}	15% BW	t_c (s)	0.199	=
	8.0 km.h^{-1}	Baseline	t_a (s)	0.089	O
	8.0 km.h^{-1}	5% BW	t_a (s)	0.078	↓
	8.0 km.h^{-1}	10% BW	t_a (s)	0.073	↓
	8.0 km.h^{-1}	15% BW	t_a (s)	0.055	↓
	10.0 km.h^{-1}	Baseline	t_a (s)	0.105	O
	10.0 km.h^{-1}	5% BW	t_a (s)	0.092	↓
	10.0 km.h^{-1}	10% BW	t_a (s)	0.088	↓
	10.0 km.h^{-1}	15% BW	t_a (s)	0.069	↓
	12.0 km.h^{-1}	Baseline	t_a (s)	0.114	O
	12.0 km.h^{-1}	5% BW	t_a (s)	0.106	↓
	12.0 km.h^{-1}	10% BW	t_a (s)	0.098	↓
	12.0 km.h^{-1}	15% BW	t_a (s)	0.078	↓
	14.0 km.h^{-1}	Baseline	t_a (s)	0.124	O
	14.0 km.h^{-1}	5% BW	t_a (s)	0.116	↓
	14.0 km.h^{-1}	10% BW	t_a (s)	0.104	↓
	14.0 km.h^{-1}	15% BW	t_a (s)	0.087	↓
	16.0 km.h^{-1}	Baseline	t_a (s)	0.128	O
	16.0 km.h^{-1}	5% BW	t_a (s)	0.121	↓
	16.0 km.h^{-1}	10% BW	t_a (s)	0.106	↓
	16.0 km.h^{-1}	15% BW	t_a (s)	0.086	↓
	8.0 km.h^{-1}	Baseline	t_{ce} (s)	0.181	O
	8.0 km.h^{-1}	5% BW	t_{ce} (s)	0.181	=
	8.0 km.h^{-1}	10% BW	t_{ce} (s)	0.174	=
	8.0 km.h^{-1}	15% BW	t_{ce} (s)	0.176	=
	10.0 km.h^{-1}	Baseline	t_{ce} (s)	0.174	O
	10.0 km.h^{-1}	5% BW	t_{ce} (s)	0.173	=
	10.0 km.h^{-1}	10% BW	t_{ce} (s)	0.170	=
	10.0 km.h^{-1}	15% BW	t_{ce} (s)	0.167	=
	12.0 km.h^{-1}	Baseline	t_{ce} (s)	0.168	O
	12.0 km.h^{-1}	5% BW	t_{ce} (s)	0.167	=
	12.0 km.h^{-1}	10% BW	t_{ce} (s)	0.161	=

12.0 km.h^{-1}	15% BW	t_{ce} (s)	0.157	=
14.0 km.h^{-1}	Baseline	t_{ce} (s)	0.160	O
14.0 km.h^{-1}	5% BW	t_{ce} (s)	0.160	=
14.0 km.h^{-1}	10% BW	t_{ce} (s)	0.155	=
14.0 km.h^{-1}	15% BW	t_{ce} (s)	0.148	=
16.0 km.h^{-1}	Baseline	t_{ce} (s)	0.150	O
16.0 km.h^{-1}	5% BW	t_{ce} (s)	0.150	=
16.0 km.h^{-1}	10% BW	t_{ce} (s)	0.145	=
16.0 km.h^{-1}	15% BW	t_{ce} (s)	0.138	=
8.0 km.h^{-1}	Baseline	t_{ae} (s)	0.194	O
8.0 km.h^{-1}	5% BW	t_{ae} (s)	0.194	↓
8.0 km.h^{-1}	10% BW	t_{ae} (s)	0.194	↓
8.0 km.h^{-1}	15% BW	t_{ae} (s)	0.186	↓
10.0 km.h^{-1}	Baseline	t_{ae} (s)	0.196	O
10.0 km.h^{-1}	5% BW	t_{ae} (s)	0.191	↓
10.0 km.h^{-1}	10% BW	t_{ae} (s)	0.193	↓
10.0 km.h^{-1}	15% BW	t_{ae} (s)	0.181	↓
12.0 km.h^{-1}	Baseline	t_{ae} (s)	0.196	O
12.0 km.h^{-1}	5% BW	t_{ae} (s)	0.188	↓
12.0 km.h^{-1}	10% BW	t_{ae} (s)	0.184	↓
12.0 km.h^{-1}	15% BW	t_{ae} (s)	0.174	↓
14.0 km.h^{-1}	Baseline	t_{ae} (s)	0.191	O
14.0 km.h^{-1}	5% BW	t_{ae} (s)	0.183	↓
14.0 km.h^{-1}	10% BW	t_{ae} (s)	0.171	↓
14.0 km.h^{-1}	15% BW	t_{ae} (s)	0.164	↓
16.0 km.h^{-1}	Baseline	t_{ae} (s)	0.187	O
16.0 km.h^{-1}	5% BW	t_{ae} (s)	0.178	↓
16.0 km.h^{-1}	10% BW	t_{ae} (s)	0.167	↓
16.0 km.h^{-1}	15% BW	t_{ae} (s)	0.148	↓
8.0 km.h^{-1}	Baseline	t_{push} (s)	0.179	O
8.0 km.h^{-1}	5% BW	t_{push} (s)	0.175	=
8.0 km.h^{-1}	10% BW	t_{push} (s)	0.180	=
8.0 km.h^{-1}	15% BW	t_{push} (s)	0.186	=
12.0 km.h^{-1}	Baseline	t_{push} (s)	0.130	O
12.0 km.h^{-1}	5% BW	t_{push} (s)	0.138	↑
12.0 km.h^{-1}	10% BW	t_{push} (s)	0.144	↑
12.0 km.h^{-1}	15% BW	t_{push} (s)	0.151	↑
16.0 km.h^{-1}	Baseline	t_{push} (s)	0.112	O
16.0 km.h^{-1}	5% BW	t_{push} (s)	0.114	↑
16.0 km.h^{-1}	10% BW	t_{push} (s)	0.122	↑
16.0 km.h^{-1}	15% BW	t_{push} (s)	0.130	↑
8.0 km.h^{-1}	Baseline	t_{brake} (s)	0.125	O
8.0 km.h^{-1}	5% BW	t_{brake} (s)	0.125	=
8.0 km.h^{-1}	10% BW	t_{brake} (s)	0.125	=
8.0 km.h^{-1}	15% BW	t_{brake} (s)	0.121	=
12.0 km.h^{-1}	Baseline	t_{brake} (s)	0.113	O
12.0 km.h^{-1}	5% BW	t_{brake} (s)	0.110	↓
12.0 km.h^{-1}	10% BW	t_{brake} (s)	0.103	↓
12.0 km.h^{-1}	15% BW	t_{brake} (s)	0.096	↓
16.0 km.h^{-1}	Baseline	t_{brake} (s)	0.098	O
16.0 km.h^{-1}	5% BW	t_{brake} (s)	0.097	↓
16.0 km.h^{-1}	10% BW	t_{brake} (s)	0.087	↓
16.0 km.h^{-1}	15% BW	t_{brake} (s)	0.073	↓

Aerial time (t_a); Body weight (BW); Braking duration (t_{brake}); Braking impulse (I_{brake}); Contact time (t_c); Effective aerial time (t_{ae}); Effective contact time (t_{ae}); Horizontal impeding forces (HIF); Mechanical Efficiency (E_{ff}); Peak braking force (Peak F_{brake}); Peak propulsive force (Peak F_{prop}); Peak vertical force (F_v); Propulsive impulse (I_{prop}); Push duration (t_{push}); Step frequency (f_{stride}); Symbol (O) is related to baseline, (↑) significant increase in comparison to baseline, (↓) significant decrease in comparison to baseline, and (=) no differences in comparison to baseline. Chang and Kram (1999) and Mesquita et al. (2020) used HIF method.

1.4.3 Asymmetries of bouncing step during running

During running on level, in the first half contact (t_{brake}), the muscles produce negative work partially storing elastic energy in the muscle-tendon units when the center of mass (BCoM) is on downward oscillation phase. The elastic energy in part is released and converted into kinetic and potential energy in the second half contact (t_{push}), when muscles produce positive work, during upward oscillation phase of BCoM. Therefore, this extra energy added minimizes the energy cost to move forward (CAVAGNA, SAIBENE and MARGARIA, 1964). The potential and kinetic energies exchange from BCoM can differentiate walking to running. Inverted pendulum is the major mechanism to saving energy during walking changing potential into kinetic energy out of phase, while in running the spring-mass model save energy when the potential and kinetic energy oscillate symmetrically in phase at a frequency (f_{syst}), compressing the spring and storing elastic energy on each step and assisting to raise and accelerate the BCoM (BLICKHAN, 1989; MCMAHON and CHENG, 1990; CAVAGNA, HEGLUND and TAYLOR, 1977).

Cavagna et al. (1988) showed that there are deviations of the symmetrical elastic bouncing in human and animals during running. When the vertical oscillation of BCoM during contact (s_c) and aerial times (s_a) was analyzed considering vertical force during running greater (s_{ce}) and lower (s_{ae}) than body weight (BW) and when contact (t_c) and aerial times (t_a) during running was considered effective or greater (t_{ce}) and lower (t_{ae}) than BW, they found there are asymmetries related to time and amplitude of BCoM oscillation that are dependent of running velocity. At lower running velocities, up to 11 km.h^{-1}, s_{ce}, t_{ce} and step frequency (f_{step}) are equal s_{ae}, t_{ae} and f_{syst} (see Figure 5). At higher running velocities, this relationship becomes asymmetrical with s_{ce}, t_{ce} and f_{step} are lower than s_{ae}, t_{ae} and f_{syst} (see Figure 6).

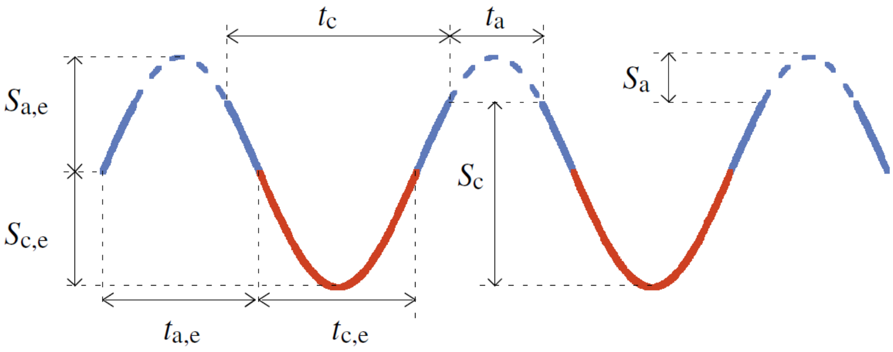

Figure 5. Symmetrical rebound (up to 11 km.h^{-1}) during vertical oscillation of BCoM (extracted from Cavagna, Heglund and Williams, 2005). Contact (t_c) and aerial times (t_a); effective contact (t_{ce}) and aerial times (t_{ae}), vertical oscillation of BCoM during contact (s_c) and aerial times (s_a).

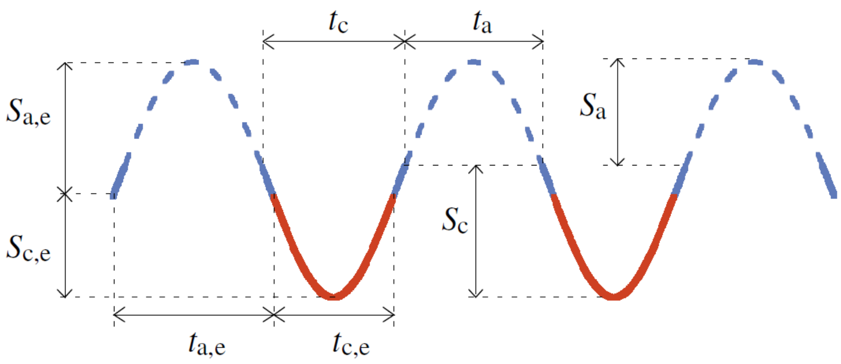

Figure 6. Asymmetrical rebound (above to 11 km.h^{-1}) during vertical oscillation of BCoM (extracted from Cavagna, Heglund and Williams, 2005). Contact (t_c) and aerial times (t_a); effective contact (t_{ce}) and aerial times (t_{ae}), vertical oscillation of BCoM during contact (s_c) and aerial times (s_a).

Extending the Cavagna et al. (1988) findings, Cavagna (2006) described in detail the asymmetries in human running. The author evaluated running mechanical variables through ground reaction forces in 10 subjects (8 males and 2 female) at running velocities 2 to 21 km.h^{-1}. It was found at low and intermediate running velocities the landing-takeoff relation is asymmetrical ($t_{push} > t_{brake}$) and becomes symmetrical ($t_{push} = t_{brake}$) at high running velocities (see Figure 7).

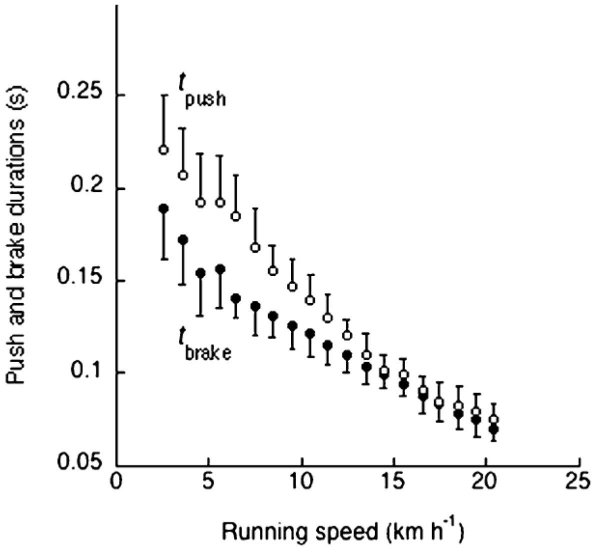

Figure 7. Push (t_{push}) and braking (t_{brake}) duration across running velocities (from Cavagna, 2009).

Conversely, the rebound is symmetrical ($t_{ae} = t_{ce}$) at low and intermediate velocities and t_{ae} values remain unchanged with increase of running velocity and t_{ce} decrease becoming this relationship asymmetrical ($t_{ae} > t_{ce}$) at high running velocities (CAVAGNA, 2009) (see Figure 8).

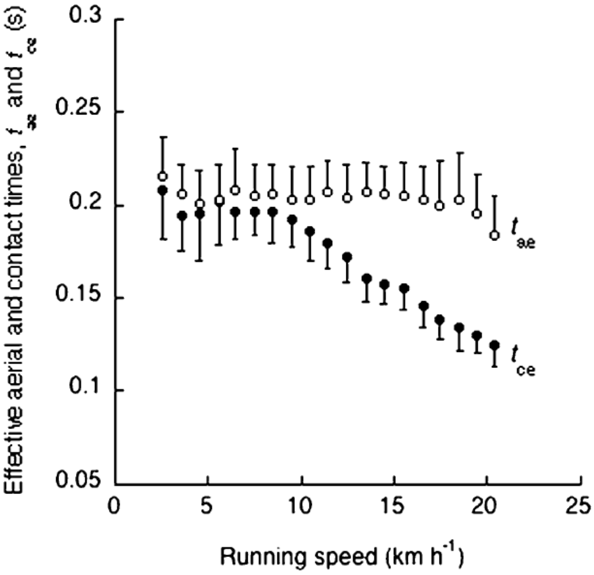

Figure 8. Effective contact (t_{ce}) and aerial times (t_{ae}) across running velocities (from Cavagna, 2009).

Regarding t_{ce}/t_{ae}, at low running velocities due to vertical momentum lost and gained, the average of vertical acceleration during t_{ce} ($\bar{a}_{v,ce}$) is equal to vertical acceleration during t_{ae} ($\bar{a}_{v,ae}$). Additionally, at low running velocities step frequency (f_{step}) is similar to the natural frequency of bouncing system (f_{syst}) and ideal for saving energy. However, at high running velocities, the t_{ce} decreases and t_{ae} remain constant and f_{step} is lower than f_{syst} because $\bar{a}_{v,ce}$ increases beyond 1g, while $\bar{a}_{v,ae}$ cannot exceed 1g. Therefore, to counterbalance the lower acceleration during t_{ae} in comparison to t_{ce} a greater t_{ae} relative to t_{ce} is needed ($t_{ae} > t_{ce}$).

In the t_{push}/t_{brake} asymmetry, at low running velocities up to 14 km.h^{-1}, the muscles act with lower activation, force, and stiffness. Therefore, the muscles are responsible substantially for stretching and shortening of muscle-tendon units during the step. At this condition, the duration of work in t_{brake} is lower than t_{push} and the force exerted during t_{brake} is greater than t_{push} (momentum lost during $t_{brake} > t_{push}$). However, at high velocities, the t_{push} is equal to t_{brake} (CAVAGNA, 2006; CAVAGNA, 2009). Cavagna suggests with increasing force and running velocity, there is an increase in t_{ce}/t_{ae} asymmetry and a decrease in t_{push}/t_{brake} asymmetry resulting in an increase in the role of tendons relative to muscle within muscle–tendon unit approaching optimal elastic bouncing in line with force-velocity muscle relation (CAVAGNA, 2009).

Some studies quantified the elastic contribution during running on aging (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008a; CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008b), level of running performance (DA ROSA et al., 2019), during human growth (LEGRAMANDI, SCHEPENS and CAVAGNA, 2013), gravity conditions (CAVAGNA, HEGLUND and WILLEMS, 2005), and against horizontal impeding forces (MESQUITA et al., 2020).

Old runners with their impaired muscle function have a loss in kinetic and potential energy transduction during upward and downward phases of BCoM oscillation in comparison to young runners. Particularly, during negative work, old runners do not have enough force to decelerate BCoM, storing less elastic energy and increasing the $t_{\mathrm{push}}/t_{\mathrm{brake}}$ asymmetry, with lower t_{a} and vertical and forward BCoM oscillation compared to young subjects. (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008a; CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008b).

The elastic bouncing is also sensitive to detect differences in the level running performance. Runners with high performance present higher t_{ae} and lower t_{ce} applying effectively more vertical force on the ground than runners with low performance (DA ROSA et al., 2019). The 3000 m level performance in these groups (low performance = 12.5 min and high performance = 10.9 min) does not differentiate in $t_{\mathrm{push}}/t_{\mathrm{brake}}$ due to a preserved neuromuscular function. These results are in line with the assumption that a reduced force and power output in the aging process harms $t_{\mathrm{push}}/t_{\mathrm{brake}}$ asymmetry (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008$_{\mathrm{a}}$), but runners with low performance and older runners resemble with low vertical oscillation of BCoM and t_{a}, and high step frequency (f_{step}) (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008$_{\mathrm{a}}$; DA ROSA et al., 2019).

Legramandi, Schepens and Cavagna (2013) compared children (2.5 years) at 8.8 km.h^{-1} and adolescents (15.8 years) at 9.4 km.h^{-1}, and they found differences associated to maturation on mechanical variables. The $t_{\mathrm{push}}/t_{\mathrm{brake}}$ and $v_{\mathrm{v,max,down}}/v_{\mathrm{v,max,up}}$ asymmetries of children group were higher due to a shorter t_{brake} and a significant decrease of total mechanical energy fluctuations (total energy = potential + kinetic vertical + kinetic forward) of BCoM during negative work phase in comparison to young subjects. Additionally, with lower body dimensions, children have high-impact collision forces and need to increase more their f_{step} than young subjects (LEGRAMANDI, SCHEPENS and CAVAGNA, 2013).

Mesquita et al. (2020) quantified the effect of high horizontal impeding forces (5, 10 and 15% of body weight) on landing-take off and rebound asymmetries during velocities from 8 to 16 km.h^{-1}. The authors found that horizontal impeding force's increment impair the elastic bouncing (t_{ae} = t_{ce} and t_{push} > t_{brake}) at high running velocities. However, paradoxically Mesquita et al. (2020) found that the highest load evaluated (15% of body weight) increased the recovery of external mechanical work by 16% at 8 km.h^{-1} (the lowest running velocity).

1.4.4 Integrative analysis of running aerodynamics

An integrative approach to quantify the effect of air resistive forces on energy cost and time saving during marathon takes into account four combined fundamentals: 1°) We need to calculate the drag forces for an elite runner at marathon pace (i.e. 5.86 m.s^{-1} for running at 2-hr marathon) (RAYLEIGH, 1876; DU BOIS and DU BOIS, 1916; PUGH, 1970); 2°) Thereafter, we need to quantify the change (%) in metabolic power to overcome small horizontal impeding forces in % of body weight (BW) across a range of running velocities; 3°) We need to use the CFD simulation data to know how optimal drafting strategies can reduce the drag forces. Polidori et al. (2020) found that shielding Kenenisa Bekele at 20.7 km.h^{-1}, three runners can reduce Bekele drag force from 7.77 to 3.32 N, therefore, 7.77/3.32 = 0.427 could be a good conversion number to apply in elite runner with similar body dimensions and running velocity; and finally, 4°) we need to quantify the energy cost and time saving of drag forces during running. The product of increase (%) in metabolic power to overcome small horizontal impeding forces (HIF) in % of BW multiplied the drag forces during running in % BW yields the increase in metabolic cost associated to drag forces (%). Additionally, with reduction in metabolic power due to drafting (- $w_{\text{power drafting}}$) see the equation below, it is possible to estimate time saving.

$$-w_{\text{power drafting}}\,(\%) = \frac{\%\text{ in metabolic power to overcome HIF }(\%\text{ BW})}{\text{reduction of drag forces due drafting }(\%\text{ BW})} \div 1 \qquad \text{Equation 6}$$

To know the time saving as result of drafting, Kipp, Kram and Hoogkamer (2019) developed a simple method to quantify the time saving in different races (10 km to Marathon events) using anthropometrics data of runner (height and body mass), the % of improvement of running economy (or - $w_{\text{power drafting}}$ in %), and race time as input. The authors used anthropometrics data to estimate A_f (m^2) and SA (%) that runners experiences air resistance during running (PUGH, 1970; DU BOIS and DU BOIS, 1916). Thereafter, they used Pugh (1971) for individualized coefficient for overcome air resistance (VO_2 ml.kg^{-1}.min^{-1} = Pugh coefficient v^3), where Pugh coefficient is equal (3.54 / body mass A_f). Additionally, they combined Pugh coefficient and the curvilinear relationship between VO_2 and running velocity to overcome air resistance (BATLINER et al., 2017):

$$\mathrm{VO_{2\,base}\,(ml.kg^{-1}.min^{-1}) = Pugh\ coefficient\ v^3 + \ 1.5355\ v^2 + 1.5374\ v + 15.661} \quad \text{Equation 7}$$

To know the improvements in running velocity, Kipp, Kram and Hoogkamer (2019) also calculated the new oxygen consumption requirements ($VO_{2\ new}$ = $VO_{2\ base}$ / (100 – RE %), where RE is % of improvement of running economy (or - $w_{\text{power drafting}}$ in %). Finally, $VO_{2\ new}$ was then set to $VO_{2\ base}$ (Equation 7) to solve the new velocity in the following equations:

$$\mathrm{VO_{2\,new}\,(ml.kg^{-1}.min^{-1}) = Pugh\ coefficient\ v^3 + \ 1.5355\ v^2 + 1.5374\ v + 15.661} \quad \text{Equation 8}$$

$$\mathrm{\%\ Improvement\ in\ velocity = (vVO_{2\,new} - vVO_{2base})/\ vVO_{2new}\ x\ 100} \quad \text{Equation 9}$$

In the Equation 9, $vVO_{2\ new}$ is the new running velocity at the new VO_2.

Several studies have simulated aerodynamics drag forces during long distance running (HOOGKAMER, KRAM and ARELLANO, 2017; HOOGKAMER, SNYDER and ARELLANO, 2018; HOOGKAMER, SNYDER and ARELLANO, 2019; KIPP, KRAM and HOOGKAMER, 2019), however, all these simulations rely on values of % in metabolic power to overcome air resistive force of studies with limited sample size (PUGH, 1971; DAVIES, 1980), they are also based on studies that applied horizontal impeding force higher than air resistive forces and low running velocities (CHANG and KRAM, 1999), or using different methods for convert aerodynamic drag forces to metabolic cost (POLIDORI et al., 2020). Future studies should focus on improvements of drag force estimations and metabolic responses in large sample of competitive runners.

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CHAPTER 2

The metabolic cost of overcoming air resistive forces in distance running in competitive male runners: a randomized crossover study

ABSTRACT

The benefits of drafting for elite marathon runners are intuitive, but the energetic and time savings are still unclear due different methods assumed for converting aerodynamic drag force reductions to metabolic power savings. We aimed to quantify how small horizontal impeding forces affect metabolic power over a range of velocities in competitive runners. Twelve male runners (age: 26.1 ± 3.5 years, mass: 66.5 ± 5.6 kg, height 1.79 ± 0.09 m) completed three data collection sessions. Subjects ran six 5-minute trials with 5 minutes of recovery in-between. We tested one velocity per session (12, 14 and 16 km.h^{-1}), at three horizontal impeding force conditions (0, 4 and 8 N). On average, metabolic power increased by 6.13% per 1% body weight (BW) of horizontal impeding force. With increasing horizontal impeding force, braking impulses decreased while propulsive impulses increased ($p < 0.001$). Across running velocities, the changes in braking and propulsive impulses with greater impeding force were correlated ($r = -0.97$; $p < 0.001$), however, these respective changes in propulsive and braking impulses were not related to individual changes in metabolic power. Based on our results, we estimate that at ~2-hour marathon pace, the metabolic cost of overcoming air resistive force comprises 8.52% of the gross metabolic power.

Keywords: drafting; horizontal impeding forces; metabolic power; performance

KEYPOINTS

- When running against horizontal impeding forces, the metabolic power requirement increases by 6.1% per 1% body weight.
- At ~2-hour marathon pace, overcoming air resistance represents about 8.5% of the total metabolic cost of running.
- At ~2-hour marathon pace, running behind an optimal practical drafting formation would be about ~4 min faster than running solo.
- Without any air resistance at all, a 2-hr marathoner could run ~7 min faster than when running solo with air resistance.

2.1 Introduction

In 2018, Eliud Kipchoge ran the official world marathon record of 2:01:39 in Berlin, and in 2019, he ran a 1:59:40 marathon in Vienna. One of the major differences between the two marathons was air resistance. In Berlin, Kipchoge ran the last 17 km without any aerodynamic drafting. In contrast, in Vienna, for the first 41 km, Kipchoge had interchanging teams of runners specifically positioned to provide substantial drafting. Drafting is the practice of having runners positioned in front of a designated runner to reduce the air resistance and hence the metabolic power requirement of the designated runner (HOOGKAMER, KRAM and ARELLANO, 2017). Drafting allows the designated athlete to run at a faster velocity with the same sustainable metabolic power (PUGH, 1971), and thereby enhancing performance (KIPP, KRAM and HOOGKAMER, 2019). Several recent studies have performed calculations and run computer simulations on the aerodynamics and energetics of running drafting (BEVES and FERGUSON, 2017; HOOGKAMER, SNYDER and ARELLANO, 2018; HOOGKAMER, SNYDER and ARELLANO, 2019; POLIDORI et al., 2020). However, each study used a different method for converting aerodynamic force to the metabolic cost of running and, hence, running performance. Given the uncertainty in previous studies, our goal was to develop an empirical equation for the metabolic power required to overcome aerodynamic drag forces and infer the performance effects.

Classic and modern methods yield remarkably similar estimates of aerodynamic drag force acting on an elite runner and the corresponding mechanical power. For a runner of Kipchoge's size running solo at 5.86 m.s^{-1} (2-hour marathon pace) in still air, the equations of Hill (1928) predict a force of 8.06 N (see Appendix S1), whereas Beves and Ferguson (2017) arrived at a value of 6.6 N using modern computational fluid dynamic (CFD) modelling. Polidori et al. (2020) also used CFD and found a value of 7.77 N for a similar-sized athlete, Kenenisa Bekele, running solo at 5.75 m.s^{-1}. A force of 7 N is just over 1% of the runners' body weights (see Appendix S1 for details). The product of the force and running velocity yields the mechanical power required to overcome aerodynamic drag. Thus, the corresponding values for mechanical power at 5.86 m.s^{-1} are also similar: 47.2 W for Hill (1928), 38.6 W for Beves and Ferguson (2017) and 44.7 W for Polidori et al. (2020). However, because these each one of these three studies used a different method for converting metabolic power, they surmised that overcoming aerodynamic drag requires 3% (HILL, 1928), 9 - 10%

(BEVES and FERGUSON, 2017), and 2.8% (POLIDORI et al., 2020) of the metabolic cost of running (see Appendix S1 for details).

A second and much more direct method of estimating the metabolic cost of overcoming air resistance involves having a runner on a treadmill in a wind tunnel with the fans turned off and on, as required, with the wind tunnel air velocity matching the treadmill belt speed. Pugh (1971) pioneered this approach and estimated that at 6 m.s^{-1}, 7.5% of the gross oxygen uptake rate is devoted to overcoming aerodynamic drag. Later, using the same method (and wind tunnel), Davies (1980) estimated that air resistance accounted for only 2% of the gross metabolic rate at 5 m.s^{-1} and 4% at 6 m.s^{-1}. While the wind tunnel studies have provided valuable insights, they were performed with very small sample sizes (n= 1 (Pugh, 1971) and n= 3 (Davies, 1980)) and thus prior to our study, we lacked an understanding of the inter-individual variation in responses.

A third conceptually very similar approach compares the metabolic power required during treadmill (i.e., no air resistance) vs. overground running. This method reveals no or little effect of air resistance at slow running velocities (MCMIKEN and DANIELS, 1976; BASSETT et al., 1985; JONES and DOUST, 1996). However, Jones and Doust (1996) found that overground running was 7% expensive at 5 m.s^{-1}. Similarly, Pugh (1970) found that at 6 m.s^{-1}, overground running required 9.2% higher oxygen uptake than treadmill running (n = 7).

Finally, scientists directly measured the increase in metabolic power consumption when horizontal impeding forces are applied to the waists of runners on a treadmill. We interpolated the results of each of these studies to quantify the per cent increase in metabolic power in response to an impeding force of 1% of body weight (BW), (see Appendix S2 for details). At a running velocity of 3.6 m.s^{-1}, Lloyd and Zacks (1972) found a 7.9% increase in metabolic power in response to an impeding force of 1% BW (n = 3). Soon thereafter, Zacks (1973) found a similar average of 7.9% increase per 1% BW impeding force at running velocities between 3.88 and 7.72 m.s^{-1} but with individual responses ranging from 5.3 to 10.6% (n = 3). However, when running at 3.3 m.s^{-1}, the results of Chang and Kram (1999) revealed an average increase in metabolic power of only 4.7% in response to 1% increase in BW impeding force (n = 10).

Given the differences in experimental approaches, the variable findings, small sample sizes, and considerable inter-subject variability in metabolic power responses to resistive forces in previous studies, we aimed to systematically quantify how small impeding forces (comparable to air resistance) affect metabolic power in a large sample of competitive runners over a range of velocities. We hypothesized that metabolic power increases linearly with increasing horizontal impeding forces. These data should facilitate accurate calculations of the effect of altered aerodynamic forces on distance running performance.

2.2 Methods

2.2.1 Participants

Twelve male runners (age: 26.1 ± 3.5 years, mass: 66.5 ± 5.6 kg, height 1.79 ± 0.09 m) participated. They all had recently run a sub-32 minute 10-km race or an equivalent performance in another distance running event. The study was performed in accordance with the ethical standards of the Declaration of Helsinki. Ethics approval was obtained from the University of Colorado Institutional Review Board (Protocol#18-0110).

2.2.2 Experimental protocol

The study consisted of three data collection sessions. During session 1, the subjects completed a health screening form and signed the informed consent form. During all three sessions, we measured the height and body weight; thereafter, the subjects warmed-up by running on a custom-built force-instrumented treadmill (KRAM et al., 1998) for 3 min at 3.33 $m.s^{-1}$ (12 $km.h^{-1}$), followed by 3 min at 3.89 $m.s^{-1}$ (14 $km.h^{-1}$). The subjects then ran six 5-minute trials with a 5 min recovery period in between. We tested one velocity per session (3.33, 3.89, or 4.44 $m.s^{-1}$ [16 $km.h^{-1}$]), at three horizontal impeding force conditions (0, 4, and 8 N). The subjects ran with each horizontal impeding force condition twice per visit, in a mirrored order, which was counterbalanced and randomly assigned. We averaged the two values for each condition.

2.2.3 Horizontal pulling apparatus

To simulate running with air resistance, we applied small horizontal impeding forces at the waist of the runners, near their center of mass (Figure 9). These forces resulted from a hanging mass that was connected via rubber tubing around pulleys to a waist belt. We used long pieces of low-stiffness natural latex rubber to minimize the bouncing of the hanging mass and force fluctuations due to length changes in the rubber tubing from slight anterior-posterior movements of the runner on the treadmill. The rubber tubing was first passed under a low-friction pulley that could be positioned vertically to match the height of the subject’s waist, ensuring that the impeding force was horizontal. The tubing was then attached to an S-beam force transducer (LCCB-50, OMEGA Engineering, INC., Norwalk, CT, USA) which measured the pulling force and fluctuations throughout the running stride. Another piece of rubber tubing was attached to the force transducer and passed over a second low-friction pulley, positioned approximately 6 m high. Hanging masses of 408 and 815 g applied impeding forces of 4 and 8 N, respectively. To counterbalance the weight of the force transducer, we added 305 grams of lead to the hanging mass. The rubber tubing dimensions differed for the two resistive force conditions: for 4 N, we used 3.2/1.2 mm (outer diameter/inner diameter); for 8 N, we used 5.6/1.2 mm. The unstretched lengths of the rubber tubing also differed such that during the running trials, the hanging mass hovered approximately 0.3 m above the floor.

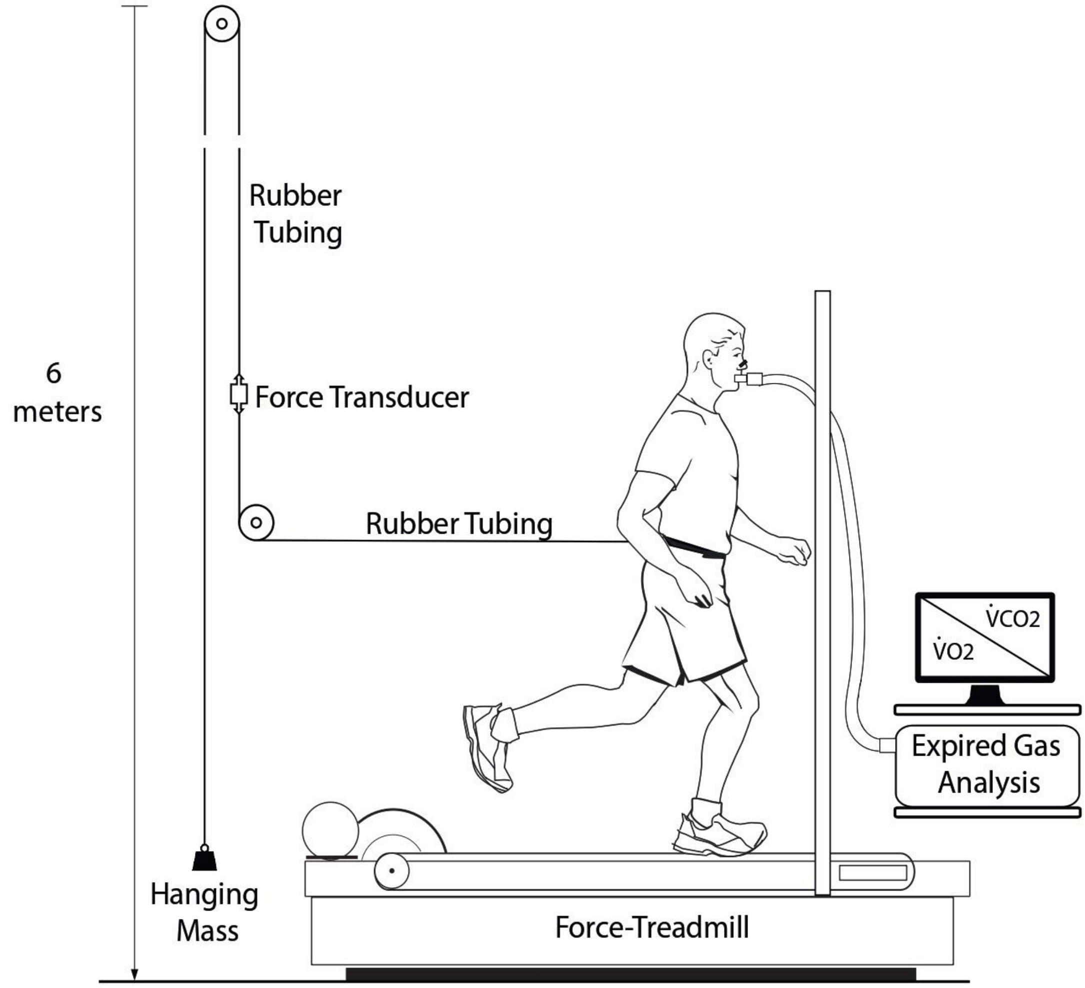

Figure 9. Experimental set-up.

2.2.4 Metabolic power protocol

During each trial, we measured the oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using a breath-by-breath expired air analysis system (True One 2400, Parvo Medics, Salt Lake City, UT, USA) and calculated the metabolic power for the last 2 min of each trial using the Péronnet and Massicotte (1991) equation. The respiratory exchange ratios ($\dot{V}CO_2/\dot{V}O_2$) remained at < 0.95 for all trials. Body mass was carefully monitored between trials, and the subjects sipped water to maintain a constant starting body mass for all trials.

2.2.5 Force measurements and analyses

We recorded the vertical (F_z) and anteroposterior (F_y) ground reaction forces and impeding force fluctuations at 1000 Hz sampling frequency for 30 s during the 2nd and 5th minutes using LabView software (National Instruments, Austin, TX, USA). In MATLAB (The MathWorks, Inc., Natick, MA, USA) we filtered the signals (low-pass 4th order Butterworth with a cutoff frequency of 25 Hz) and we used the $F_z = 30$ N threshold to determine touchdown and takeoff events (HOOGKAMER et al., 2018). We calculated peak braking and propulsive forces, peak of vertical force, braking and propulsive impulses, step frequency, duty factor, and contact time.

2.2.6 Apparent mechanical efficiency

We calculated the external mechanical power (W) by multiplying the horizontal impeding force (N) by the running velocity ($m.s^{-1}$). For each runner, we calculated the "apparent mechanical efficiency" for each impeding force at all three running velocities as the change in external mechanical power (W/kg) from unloaded running over the change in metabolic power (W/kg) from unloaded running (LLOYD and ZACKS, 1972).

2.2.7 Statistics

We compared the metabolic power, temporal and kinetic variables between the three running velocities and the three horizontal impeding force conditions using two-way ANOVA with repeated measures. When significant main or interaction effects were detected, we performed Bonferroni corrected paired t-tests to determine *post-hoc* which velocity and/or horizontal impeding force comparisons differed significantly. We also explored whether inter-individual difference in the increases in metabolic power with horizontal impeding force were related to changes in braking or propulsive impulses with horizontal impeding force using linear regression analysis. We used traditional levels of significance ($\alpha = 0.05$ and $\alpha_{post\text{-}hoc} = 0.0167$) and performed analyses with Statistical Package for the Social Sciences 22.0 (IBM Corporation, Inc., New York, United States).

2.3 Results

Metabolic power was significantly high at fast running velocities ($p < 0.001$), and with large horizontal impeding forces ($p < 0.001$), with a significant interaction effect ($p < 0.001$); Figure 10, see Electronic Supplementary Material Appendix S3 for a Table with individual data)). The interaction effects were that in response to a specific horizontal impeding force, metabolic power increased more at faster running velocities (12, 14, and 16 km.h^{-1}; $p < 0.001$) and at a specific velocity, metabolic power increased more with larger horizontal impeding force [baseline, 4 N, and 8 N ($p < 0.001$)].

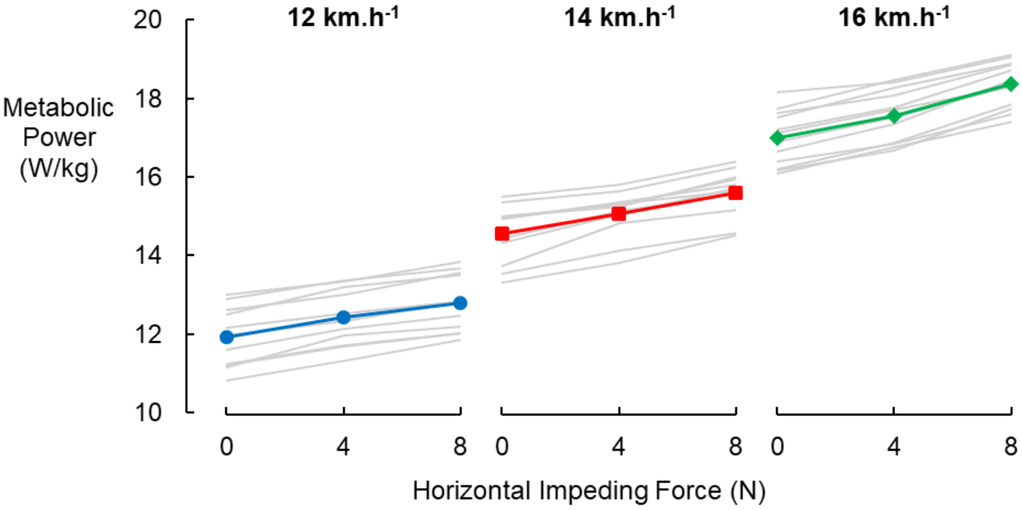

Figure 10. Metabolic power (W/kg) vs. horizontal impeding force (N) for each runner (gray) and the group means (colored symbols) for each of the three velocities tested.

At each velocity, metabolic power increased linearly with increasing horizontal impeding force expressed relative to BW (Figure 11); second order polynomial fitting did not substantially improve the R^2 values.

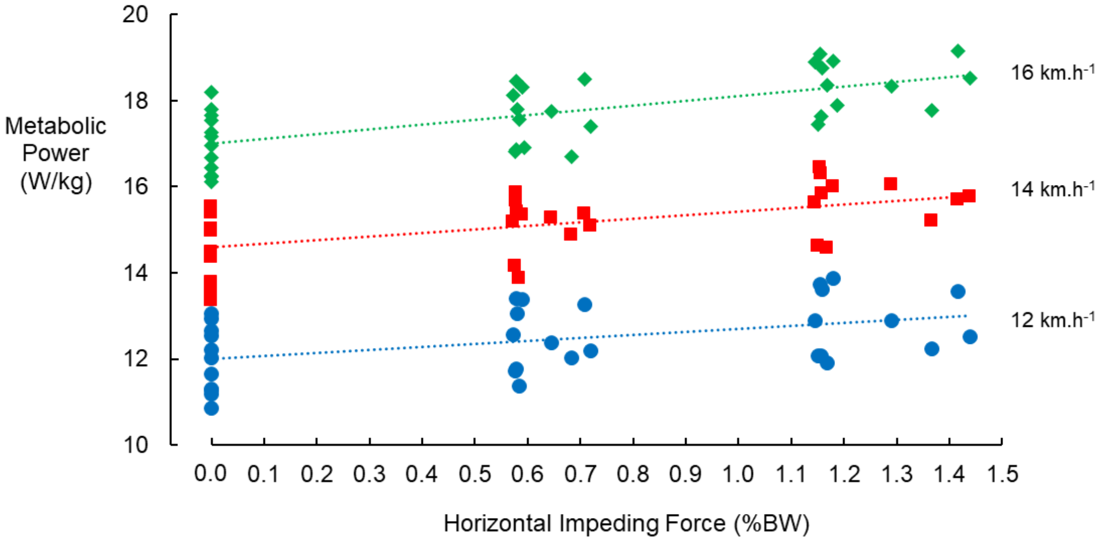

Figure 11. Metabolic power (W/kg) vs. horizontal impeding force (HIF) (% body weight). Blue circles represent individual subjects at 12 km.h^{-1}, red squares 14 km.h^{-1} and green diamonds 16 km.h^{-1}. Dotted lines are the linear best fit regressions at each velocity: at 12 km.h^{-1} [W/kg = 0.6977 HIF + 11.996 ($R^2 = 0.2004$)], at 14 km.h^{-1} [W/kg = 0.8386 HIF + 14.594 ($R^2 = 0.3193$)] and at 16 km.h^{-1} [W/kg = 1.1048 HIF + 16.993 ($R^2 = 0.4478$)].

Across the runners, the average increase in metabolic rate was 6.13% per 1% BW horizontal impeding force. This was consistent across the three tested running velocities with 6.14, 5.87, and 6.37% slopes for 12, 14, and 16 km.h^{-1}, respectively. Notably, relative changes in metabolic power with horizontal impeding force varied substantially between individual runners (Figure 12), ranging from 4.75 to 8.14%.

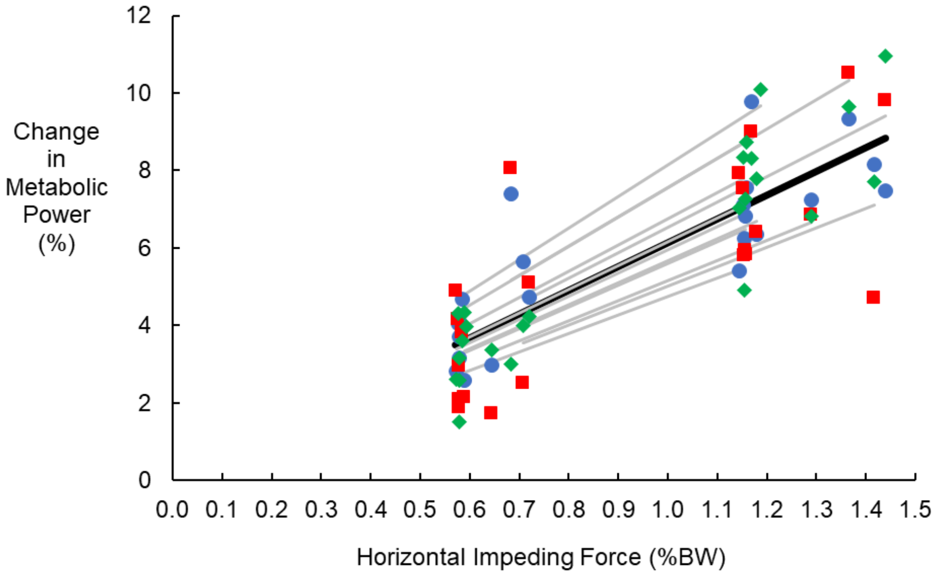

Figure 12. Per cent increase in metabolic power (%) with horizontal impeding force (HIF) (% body weight). Blue circles represent individual subjects at 12 km.h^{-1}, red squares 14 km.h^{-1} and green diamonds 16 km.h^{-1}. For each individual, the best linear fit through the origin is shown in gray. The black line represents the best fit through

all the data [% change = 6.13 HIF ($R^2 = 0.68$)]. Regressions were forced to go through the origin but zero HIF data points were not included in the regression analysis.

Apparent mechanical efficiency was also consistent across the tested velocities ($p = 0.401$). At the slowest running velocity (12 $km.h^{-1}$), the apparent mechanical efficiency was 43.6 ± 10.1% from 0 to 4 N and 46.5 ± 5.9% for 0 to 8 N. At intermediate and fast running velocities, the apparent mechanical efficiencies were numerically lower for the stronger impeding forces (14 $km.h^{-1}$: 55.2 ± 22.6% for 0 to 4 N and 46.6 ± 11.3% for 0 to 8 N; 16 $km.h^{-1}$: 50.1 ± 15.5% for 0 to 4 N and 40.0 ± 7.0% for 0 to 8 N), but these effects were not significant (main effect of impeding force: $p = 0.062$; interaction effect of velocity impeding force: $p = 0.066$).

Table 3. Temporal kinematic data for different horizontal impeding force (HIF) conditions

Running Velocity ($km.h^{-1}$)	HIF (N)	Step Frequency (Hz)	Contact Time (s)	Duty Factor
12	0	2.91 ± 0.12	0.228 ± 0.011	0.33 ± 0.02
	-4	2.91 ± 0.12	0.228 ± 0.012	0.33 ± 0.02
	-8	2.92 ± 0.11	0.227 ± 0.012	0.33 ± 0.02
14	0	2.95 ± 0.12	0.210 ± 0.010	0.31 ± 0.02
	-4	2.95 ± 0.11	0.210 ± 0.010	0.31 ± 0.02
	-8	2.96 ± 0.09	0.210 ± 0.010	0.31 ± 0.02
16	0	2.98 ± 0.10	0.193 ± 0.009	0.29 ± 0.02
	-4	2.99 ± 0.10	0.192 ± 0.009	0.29 ± 0.02
	-8	3.01 ± 0.09	0.192 ± 0.010	0.29 ± 0.02

Step frequency, contact time, and duty factor were all independent of horizontal impeding forces ($p = 0.061$, $p = 0.091$, and $p = 0.786$, respectively), but the step frequency increased, and the contact time and duty factor decreased with running velocity ($p = 0.010$, $p < 0.001$, and $p < 0.001$, respectively; Table 3).

Table 4. Kinetic data for different horizontal impeding force (HIF) conditions

Running Velocity (km.h^{-1})	HIF (N)	Braking Impulse (N·s)	Propulsive Impulse (N·s)	Peak Braking Force (N)	Peak Propulsive Force (N)	Peak Vertical Force (N)
12	0	12.7 ± 1.3	12.7 ± 1.3	232 ± 31	183 ± 24	1663 ± 222
	-4	12.0 ± 1.0	13.4 ± 1.0	226 ± 29	190 ± 25	1666 ± 223
	-8	10.8 ± 1.3	13.6 ± 1.3	215 ± 30	195 ± 25	1662 ± 218
14	0	13.9 ± 1.2	13.9 ± 1.2	264 ± 28	224 ± 28	1752 ± 229
	-4	12.9 ± 1.1	14.2 ± 1.1	257 ± 29	227 ± 25	1741 ± 220
	-8	12.1 ± 1.2	14.8 ± 1.2	249 ± 28	232 ± 27	1738 ± 225
16	0	14.9 ± 0.9	14.9 ± 0.9	302 ± 30	266 ± 27	1878 ± 218
	-4	14.1 ± 1.4	15.4 ± 1.4	289 ± 27	273 ± 30	1867 ± 206
	-8	13.1 ± 1.3	15.8 ± 1.3	279 ± 34	278 ± 25	1857 ± 212

With increasing horizontal impeding force, braking impulses decreased while propulsive impulses increased (both $p < 0.001$; Table 4). Braking and propulsive impulses both increased with fast running velocities (both $p < 0.001$). Peak braking and propulsive forces paralleled those changes (all $p < 0.001$) (Figure 13). Peak vertical force was independent of horizontal impeding force ($p = 0.140$) and increased at fast running velocities ($p < 0.001$). Across the running velocities, the changes in braking and propulsive impulses with high impeding forces were correlated ($r = -0.97$; $p < 0.001$), indicating that runners who overcame the horizontal impeding forces without reducing their braking impulses substantially, increased their propulsive impulses to a large extent. However, these changes in propulsive and braking impulses were not related to individual changes in metabolic power ($p = 0.554$ and $p = 0.640$, respectively).

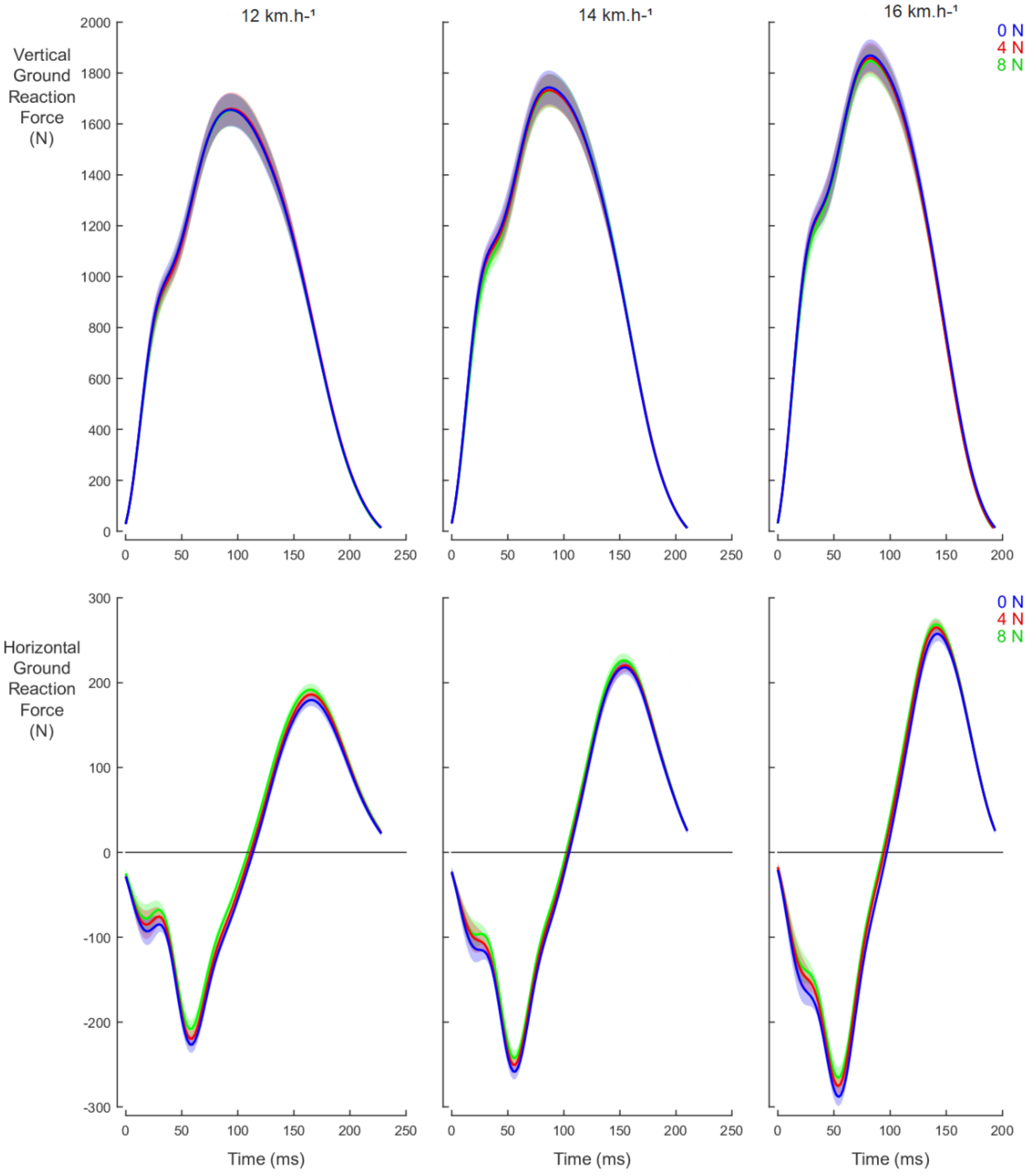

Figure 13. Mean and standard deviation of vertical and anteroposterior ground reaction forces at the three running velocities (12, 14 and 16 km.h^{-1}) and horizontal impeding forces (0, 4 and 8 N).

2.4 Discussion

The purpose of our study was to quantify how small resistive forces, similar in magnitude to aerodynamic forces, affect the metabolic power required to run across a range of running velocities. We applied horizontal impeding forces of 0, 4, and 8 N while 12 competitive male runners ran at 12, 14 and 16 km.h^{-1}. On average, metabolic power increased by 6.13% per 1% BW horizontal impeding force, but with substantial inter-individual differences, whereby the values ranged from 4.75% to 8.14%.

What does this mean for elite marathon running performance? First, we estimated that the drag force experienced by Eliud Kipchoge running solo at 2-hr pace (5.86 $m.s^{-1}$) equates to 7.75 N or 1.52% BW, using Lord Rayleigh's drag force equation (RAYLEIGH, 1876) and surface and projected frontal area estimates (DU BOIS and DU BOIS, 1916; PUGH, 1971) (see Appendix S4). A drag force of 1.52% BW indicates that 8.52% of metabolic power during overground running is devoted to overcoming aerodynamic drag. Polidori et al. (2020), using CFD found that with an optimal practical drafting formation, drag forces would be reduced by 57.3%. Our data indicates that at 2-hr marathon pace such a reduction in drag force would result in a 5.34% metabolic savings (see Appendix S4). Using the metabolic savings to time savings conversion from Kipp, Kram and Hoogkamer (2019), at 2-hr marathon pace, running behind an optimal practical drafting formation would be about 4 min (4:03) faster than solo running. In the theoretical scenario of zero air resistance, our data predict that a 2-hr marathoner could run about 7 min (7:05) faster than running solo without drafting.

For an elite female runner with dimensions of world record holder Brigid Kosgei, running at 2:15 marathon pace (5.21 $m.s^{-1}$), overcoming air resistance constitutes 7.09% of her total metabolic power. Using similar calculations suggests that at 2:15 marathon pace, optimal realistic drafting is also about 4 min (3:57) faster than solo running and running with zero air resistance would save 6:53 minutes (see Appendix S4).

When Eliud Kipchoge broke the 2-hr marathon barrier in Vienna, he was able to draft for the full marathon distance by having teams of pacers take turns in shielding him. Similarly, in mixed gender races, elite women can theoretically draft behind men for the full marathon distance. However, in major marathons with separate races for the elite men and women, the top finishers rarely can draft beyond the first 32 km because designated pacers become exhausted. Our data imply that an additional 10 km of optimal practical drafting could result in a 1-minute faster marathon time. This suggests that substantial time savings might be possible with creative drafting strategies such as a rotating pace line which is common in cycling (HOOGKAMER, SNYDER and ARELLANO, 2018).

For perspective, we applied our results to recreational marathoners running 3, 4, or 5 hours (using mean body mass (65.6 kg) and height (1.75 m)) for a 3-hr marathoner (GORDON et al., 2017). The overall metabolic cost associated with overcoming drag force at these slower marathon paces equates to, respectively, 3.61, 2.06 and 1.33% of the total metabolic power. Similarly, the time reductions from hypothetical optimal drafting (no air resistance) are 1.77, 1.26 and 1.01% for 3, 4 and 5-hr marathon pace, respectively. These substantial differences in the relative metabolic cost of overcoming the air resistive force between 5-hr (2.37 $m.s^{-1}$) and 2-hr pace (5.86 $m.s^{-1}$) can be attributed mainly to the increase in air drag force which is proportional to in velocity squared (HILL, 1928). Interesting, the actual time savings in minutes are fairly similar for 2-hr and 5-hr marathoners (between 4 and 3 min).

We found that metabolic power increased by 6.13% for each 1% BW of horizontal impeding forces. Our results are well within the range of previous results of studies using horizontal impeding forces during running, which found 4.7% to 7.9% increase per 1% BW (CHANG and KRAM, 1999; LLOYD and ZACKS, 1972; ZACKS, 1973). For an air drag force of 1.52% BW at 5.86 $m.s^{-1}$, our data indicates a 9.32% increase in metabolic power, slightly higher than the 7% (at 5 $m.s^{-1}$) and very close to the 9.2% (at 6.0 $m.s^{-1}$) increases in oxygen uptake reported by Jones and Doust (1996) and Pugh (1970), respectively. Additionally, as mentioned before, our data indicates that 8.52% of metabolic power during overground running is devoted to overcoming aerodynamic drag, which is close to wind tunnel results from Pugh (1971) who calculated 7.5% at 6.0 $m.s^{-1}$ (extrapolated from observations at 4.47 $m.s^{-1}$), but substantially higher than the 4% at 6 $m.s^{-1}$ that Davies (1980) reported based on experiments in the same wind tunnel.

In the present study, we found that braking impulses decreased while propulsive impulses increased with horizontal impeding force. Peak braking and propulsive forces paralleled those changes. In addition, there were no effects of horizontal impeding force on the step frequency, contact time or duty factor. These results are in line with Chang and Kram (1999), who evaluated the effect of horizontal impeding forces (0, 3, and 6% BW) at 3.3 $m.s^{-1}$ on oxygen uptake and ground reaction forces in well-trained runners. They found the same relation between horizontal impeding forces and braking and propulsive impulses and between peak of braking and propulsive forces, without effects on the peak of vertical forces, stride frequency, contact time or duty factor.

It has been suggested that running with horizontal impeding forces is like to uphill running (JONES and DOUST, 1996; BIJKER, GROOT and HOLLANDER, 2001). During steady state, level treadmill running braking and propulsive impulses must be equal and opposite; however, on an incline, propulsive impulses increase while braking impulses decrease (GOTTSCHALL and KRAM, 2005), similarly to what we and Chang and Kram (1999) observed for running with horizontal impeding forces. Furthermore, apparent mechanical efficiency is similar between uphill at a 1% incline and running with horizontal impeding forces like to the gravitational component parallel to the surface during uphill running (BIJKER, GROOT and HOLLANDER, 2001).

Substantial variations in apparent mechanical efficiency have been reported in the literature for running, mainly related to different methods of mechanical power calculation, muscle efficiency (relation between phosphorylation and contraction coupling), baseline assumption for energy cost and elastic energy storage (CAVANAGH and KRAM, 1985a; CAVANAGH and KRAM, 1985b; KANEKO, 1990). We did not find systematic effects of horizontal impending force and running velocity on apparent efficiency with values ranging from 40% to 55%. Our results are in line with Bijker, Groot and Hollander (2001), who observed an apparent efficiency of 46% with extra mechanical power up to 120 W at a running velocity of 8 km.h^{-1} and Asmussen and Bonde-Petersen (1974) who observed an apparent efficiency of 54% for running velocity of 10 km.h^{-1} and extra mechanical power of 69.7 W. However, Lloyd and Zacks (1972) found a lower apparent efficiency (36%) than the abovementioned authors during 13 km.h^{-1} and extra mechanical power up to 190 W, which is close to Zacks (1973) who reported 39% apparent efficiency for running velocities between 14 and 17 km.h^{-1} and external mechanical power of 46 – 61 W. Still, all these apparent efficiency values are substantially higher than in cycling (BIJKER, GROOT and HOLLANDER, 2001) and higher than efficiency values for concentric muscle contractions (SMITH, BARCLAY and LOISELLE, 2005). For uphill running, Hoogkamer, Taboga and Kram (2014) explained this discrepancy by accounting for the fact that during uphill running, braking impulses decrease, and thus smaller propulsive impulses are needed to compensate for these smaller braking impulses. During uphill running, the metabolic power associated with generating these smaller braking impulses and the smaller cost of the propulsive compensating impulses, will be lower than during level running. As a result, the change in metabolic power from level to uphill running underestimates the actual metabolic power required to generate the external mechanical power. Future research should address if this concept can also explain the high efficiency values found for running with horizontal impeding forces.

Our study has some limitations worthy of mention. We applied horizontal impeding forces applied at the waist (center of mass), but air resistive forces during running are spread out over the body. The different shapes of body segments can produce different drag coefficients in specific areas of the body and therefore drag forces vary between segments (SHANEBROOK and JASZCZAK, 1976). Future wind tunnel studies are needed to fully validate our findings. In addition, we used fixed horizontal impeding forces (4 and 8 N) across subjects, which represent an average of 0.62 and 1.23% of BW for our subjects (respectively), but ranged from 0.57 to 0.72% BW for 4 N and from 1.15 to 1.44% BW for 8 N. Our predictions for marathon running performance used specific assumptions to calculate air drag force (sea level, 20° C, see Electronic Supplementary Material Appendix S4) and should be adjusted for other conditions. Finally, for our calculations, we assumed that the relative air velocity was equal to the running velocity, but even on calm days, air is never perfectly stationary. Related to this, future studies should evaluate the metabolic cost of running with different wind directions, such as cross wind and tailwind effects, either using an experiment set-up similar to ours or when feasible in a wind tunnel.

2.5 Conclusion

We found that metabolic power increased by 6.13% per 1% BW of horizontal impeding force. Based on our results, we estimate the metabolic cost for overcoming air resistive force at 2-hour marathon pace comprises 8.52% of the total metabolic power, and that for a marathon at this pace, the difference between the optimal practical drafting formation and solo running is ~4 min.

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2.6 References

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2.7 Appendix S1

This Appendix addresses several topics. First, we explain in detail how we derived the aerodynamic drag force values from the previous articles which we presented in the Introduction section of this paper. Second, we discuss in more detail how previous articles converted mechanical power estimates to metabolic energy savings.

In a classic study, Hill (1928) measured the air resistance forces acting on a scaled physical model of a runner (0.2 m tall) in a small wind tunnel and provided generalized equations for the aerodynamic drag force using only the runner's height (H) and velocity (*v*) as inputs. Hill provided the formula 0.15 h^2 for frontal area (A_f). Using Kipchoge's height of 1.67 m yields a frontal area of 0.418 m^2. The standard equation for aerodynamic drag force (F) (RAYLEIGH, 1876) in N is:

$$\mathrm{F} = 0.5\ \mathrm{A_f}\ \mathrm{C_d}\ \rho\ \mathrm{v}^2 \qquad \text{Equation A1}$$

Hill used a C_d (coefficient of drag) of 0.9 and air density (ρ) of 1.247 kg/m^3. Applying Hill's equation to Kipchoge running solo at a velocity (v) of 5.86 $m.s^{-1}$ (2-hr marathon pace) yields a force of 8.06 N. Beves and Ferguson (2017) used computational fluid dynamic (CFD) modelling to estimate the force acting on Kipchoge running solo at 5.86 $m.s^{-1}$ as 6.6 N but they did not provide the details behind that value and their simulated depiction of Kipchoge was unrealistically corpulent. Polidori et al. (2020) used CFD to calculate the air resistance acting on Kenenisa Bekele (the second fastest marathoner to date) running solo at 5.75 $m.s^{-1}$. They determined a frontal area of 0.475 m^2 and used a C_d of 0.812 and air density of 1.219 kg/m^3. Bekele is slightly shorter and heavier (1.65 m and 56 kg) than Kipchoge. Thus, Polidori et al. (2020) calculated an aerodynamic drag force of 7.77 N for Bekele.

All three studies described above converted their similar force values first to external mechanical power to then use mechanical efficiency to calculate metabolic power. Multiplying aerodynamic drag force by the running velocity yields mechanical power. Hill's (1928) equations yield 47.2 W of mechanical power for Kipchoge running solo at 5.86 $m.s^{-1}$, Beves and Ferguson (2017) calculated 38.6 W for Kipchoge solo at 5.86 $m.s^{-1}$ and Polidori et al. (2020) found 44.7 W for Bekele solo at the slightly slower velocity (5.75 $m.s^{-1}$).

Each of the three studies used different efficiency values. Efficiency is typically calculated as the mechanical power produced divided by the metabolic power required. Hill estimated that a 72.5 kg runner “at longer distances” (unspecified velocity) would have an oxygen uptake of ~4L O_2/min (~55 mlO_2/kg/min) to provide metabolic power for all of the physiological processes involved in running. That is considerably lower than the ~70 $ml.kg^{-1}.min^{-1}$ of modern, world-class marathoners (JONES et al., 2020). Hill converted that oxygen uptake of ~4L O_2/min to metabolic power assuming exclusively glycogen as the fuel substrate, arriving a value of 1459 W. Hill then divided 47.2 W of *mechanical* power for just aerodynamic power by the 1459 W of total *metabolic* power required (implicitly, incorrectly assuming an apparent mechanical efficiency of 100%) and concluded that overcoming air resistance comprises only ~3% of the total metabolic power.

Beves and Ferguson’s (2017) model found that when optimally drafting, Kipchoge only needed to produce 10.5 W of mechanical power to overcome drag (a reduction of 28.1 W from solo). Beves and Ferguson then used a value of 300 W for Kipchoge’s sustainable mechanical power which was based on a blogger who used typical values for bicycling. Beves and Ferguson divided the reduction of 28.1 W of mechanical power due to drafting by 300 W of total (cycling) mechanical power yielding a 9 to 10% improvement in running performance compared to running solo. Clearly it is inappropriate to apply a value for cycling to a running.

Polidori et al. (2020) took yet another approach. They began with the CFD estimate for the total mechanical power requirement of 899.6 W when running solo from an equation of Cavagna and Kaneko (1977) and 874.0 W in the optimal drafting configuration (from subtracting their CFD simulation results for aerodynamic power from that number). They then used a 63% value for human running efficiency (CAVAGNA and KANEKO, 1977) and arrived at 2.8% savings in metabolic power possible with optimal drafting. However, the 63% efficiency value is probably high, in part because it ignores the importance of elastic energy storage and recovery from the tendons in human running (CAVANAGH and KRAM, 1985).

Regardless of the details, the Hill (1928), Beves and Ferguson (2017) and Polidori et al. (2020) approaches are intrinsically flawed because the metabolic cost of running is determined by muscular force (KRAM and TAYLOR, 1990; KIPP, GRABOWSKI and KRAM, 2018) and not mechanical power (HEGLUND et al., 1982).

2.9 Appendix S2

Relative increase in metabolic power per %BW

To be able compare the findings of Lloyd and Zacks (1972), Zacks (1973) and Chang and Kram (1999), we calculated the relative increases in metabolic power per % BW of resistive force. For Lloyd and Zacks (1972) and Zacks (1973), we used values for apparent efficiency, metabolic power during “zero-load” running and running velocity reported in Table 2 of each study (as LRE, E_k and mean speed, respectively). For Chang and Kram (1999), we converted oxygen uptake to metabolic power.

These calculations were straight forward for Chang and Kram (1999). They reported data for 8 well-trained recreational runners (5 men and 3 women; 65.8 ± 9.3 kg) that ran at a fixed velocity of 3.3 $m.s^{-1}$ (11.9 $km.h^{-1}$) with horizontal impeding forces of 3 and 6% BW. We converted oxygen uptake expressed in $ml.kg^{-1}.min^{-1}$ into metabolic power (W/kg) by multiplying the average values of oxygen uptake for each condition by 20.9 J/ml oxygen and dividing by 60 seconds/min. Based on the changes in metabolic rate for horizontal impeding forces of 3 and 6%BW we calculated an average relative increase of 4.7% in metabolic power per 1%BW.

Lloyd and Zacks (1972) reported data of 3 male well trained cross-country and track athletes (57.2 ± 0.9 kg) who ran at velocities up to 13 $km.h^{-1}$ with horizontal impeding forces ranging from 2.2 to 9.6 %BW (12.2 to 54.0 N). Zacks (1973) reported data for 3 athletes (62.3 ± 9.7 kg) who ran at velocities ranging from 14 to 17 $km.h^{-1}$ with horizontal impeding forces ranging from 1.6 to 2.6 % BW (9.8 to 15.7 N). Each athlete ran at several different velocities, and with multiple loads at each velocity. For each velocity, the runner’s metabolic cost during running without resistive forces (E_k in kcal/kg/km) and the average apparent efficiency (%) were reported.

First, we converted E_k to J/kg/km (factor of 4184 J/kcal). Then, we calculated metabolic power in W/kg by multiplying E_k in J/kg/km by the running velocity in km/s. Next, we set out to determine the resistive force in % BW and the external mechanical power in W/kg, but Lloyd and Zacks (1972) did not provide detailed information about their hanging mass conditions. Instead, we assumed a maximum reported external mechanical power of 70 W for all speeds and calculated the hanging mass that would provide that at each velocity. Zacks (1973) states that “At speeds of 14 and 17 $km.h^{-1}$ the maximum loads were about 1.6 and 1 kg respectively”. We assumed a linear relation between velocity and hanging mass to determine the maximum loads at the other velocities. For each velocity, we then calculated the external mechanical power.

Based on the maximum external mechanical power and the reported average apparent efficiency, we calculated the increase in metabolic power beyond unloaded running. Next, we calculated the relative increase in metabolic power. Finally, we calculated the relative increase in metabolic power per % BW of resistive force. For both studies these calculations resulted in an average relative increase of 7.9% in metabolic power per 1% BW.

2.8 Appendix S3

Supplementary Table

Table S1. Mean gross metabolic power (W/kg) data for different horizontal impeding forces at the three velocities for each of the 12 subjects tested in the present study.

	12 km.h^{-1}			14 km.h^{-1}			16 km.h^{-1}		
	0 N	-4 N	-8 N	0 N	-4 N	-8 N	0 N	-4 N	-8 N
1	13.05	13.39	13.88	15.03	15.35	15.99	17.55	18.32	18.92
2	12.22	12.56	12.88	14.48	15.18	15.62	17.66	18.12	18.90
3	11.19	12.02	12.24	13.77	14.88	15.21	16.22	16.71	17.79
4	12.65	13.05	13.61	14.97	15.41	15.84	17.26	17.80	18.77
5	12.54	13.25	13.57	14.99	15.36	15.69	17.79	18.50	19.16
6	11.27	11.72	12.07	13.59	14.16	14.62	16.11	16.81	17.46
7	12.93	13.41	13.73	15.54	15.86	16.44	18.19	18.46	19.08
8	-	-	-	-	-	-	16.25	16.90	17.90
9	11.64	12.19	12.51	14.36	15.09	15.77	16.69	17.39	18.51
10	12.02	12.38	12.89	15.02	15.28	16.05	17.17	17.75	18.34
11	11.30	11.76	12.07	15.39	15.68	16.30	16.45	16.87	17.65
12	10.86	11.36	11.92	13.37	13.88	14.57	16.95	17.56	18.36

2.9 Appendix S4

Drag forces at marathon pace

First, we calculated the surface area (SA) for different marathoners using height (H) in cm and body mass (M) in kg, using the Du Bois and Du Bois (1916) equation:

$$\mathrm{SA} = 0.007184\ \mathrm{H}^{0.725}\ \mathrm{M}^{0.425} \qquad \text{Equation A1}$$

Next, we calculated the projected frontal area (A_f) based on Pugh (1970):

$$\mathrm{A_f} = 26.6\%\ \mathrm{SA} \qquad \text{Equation A2}$$

In Table S2, the surface and frontal area for an elite male runner with dimensions of Eliud Kipchoge and an elite female runner with dimensions of Brigid Kosgei are presented. Additionally, we used anthropometric data (mass and height) for a typical recreational runner from Gordon et al. (2017).

Table S2. Surface and frontal area of marathon runners:

Runners	Body mass (kg)	Height (cm)	Surface area (m²)	Frontal area (m²)
Eliud Kipchoge	52	167	1.567	0.417
Brigid Kosgei	50	170	1.561	0.415
3-hr	65.6	175	1.788	0.476
4-hr	65.6	175	1.788	0.476
5-hr	65.6	175	1.788	0.476

Finally, we used Lord Rayleigh’s drag force equation (RAYLEIGH, 1876):

$$\mathrm{F} = 0.5\ \mathrm{A_f}\ \mathrm{C_d}\ \rho\ \mathrm{v}^2 \qquad \text{Equation A3}$$

Where A_f is projected frontal area (m), C_d is the coefficient of drag, ρ is air density (in kg/m³), *v* is running velocity (in m.s^{-1}). At sea level the density of air at 20° C is 1.204 (KYLE and CAIOZZO, 1986); for C_d, we used 0.9 (HILL, 1928). Additionally, we calculated the drag force (F) in % of body weight (BW). The results are presented in Table S3:

Table S3. Drag force (F) for marathon runners:

Runners	Time (hr/min/sec)	Velocity (m.s^{-1})	Drag force (N)	Drag force (% BW)
Eliud Kipchoge	2:00:00	5.86	7.75	1.52

Brigid Kosgei	2:15:00	5.21	6.10	1.24
3-hr	3:00:00	3.91	3.93	0.61
4-hr	4:00:00	2.93	2.21	0.34
5-hr	5:00:00	2.34	1.42	0.22

Drafting, metabolic cost and time saving of drag forces

To estimate drag forces of running during drafting, we used reference values of Computational Fluid Dynamics simulations for an elite male runner with a best marathon performance very similar to Eliud Kipchoge (Kenenisa Bekele) (POLIDORI et al., 2020). Polidori et al. (2020) simulated different drafting scenarios, such as running alone (7.77 N) and running behind the middle pacer of three side-by-side pacers (3.32 N). We divided both values (3.32 / 7.77 = 0.427) to estimate the drag forces during “optimal practical drafting” for the five different scenarios in Table S3.

Next, we calculated the reduction in drag forces due to drafting (N) in % BW. Based on our main findings we calculated the metabolic savings from drafting by multiplying this by 6.13% (the relative increase in metabolic power for running with 1% of BW of horizontal impeding forces (Figure 12). To predict the time savings from drafting at marathon pace, we used the simple method proposed by Kipp, Kram and Hoogkamer (2019), using height (m), body mass (kg), improvement in running economy (%) and marathon time as inputs. Additionally, we used the same equations described above to calculate elite marathon performances in the hypothetical scenario of running with zero air resistance, for example in a vacuum or on treadmill (less hypothetical). In this scenario, the reduction in metabolic power of drafting is 9.32% and the time saving would be about 7 min (7:05) for a 2-hr male marathoner and 7.63% or 6:53 min for a 2:15 female marathoner, respectively (Table S4).

Finally, we calculated how much of the total the metabolic cost of running is due to overcoming air resistance, based on the air drag force experienced when running solo:

$$\frac{\text{Additional metabolic cost of overcoming air resistance (\%)}}{100\% + \text{Additional metabolic cost of overcoming air resistance (\%)}} * 100\% \qquad \text{Equation A4}$$

Table S4. Metabolic cost and time savings for marathon runners:

Runner	Drag force while drafting (N)	Reduction in metabolic power while drafting (%)	New velocity (m.s^{-1})	Time savings min:sec	Relative metabolic cost of overcoming air resistance (%)
Eliud Kipchoge	3.31	5.34	6.07	4:03	8.52
Eliud Kipchoge (Treadmill)	0	9.32	6.23	7:05	8.52
Brigid Kosgei	2.61	4.37	5.37	3:57	7.09
Brigid Kosgei (Treadmill)	0	7.63	5.49	6:53	7.09
3-hr	1.68	2.15	3.98	3:08	3.61
4-hr	0.94	1.21	2.97	2:59	2.06
5-hr	0.60	0.77	2.37	3:00	1.33

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CHAPTER 3

The effect of small horizontal impeding force on spring-mass model and asymmetries of bouncing step in long-distance runners: a randomized crossover study

ABSTRACT

Running against heavy horizontal impeding forces (15% of body weight) changes kinetic and potential energy transduction and then recovery up to 16% external mechanical work. There is a lack of evidence regarding energy saving with small impeding forces comparable to air resistance. We aimed to quantify how small horizontal impeding forces can save energy by spring-mass model and asymmetries of bouncing step (rebound and landing take-off) in long-distance runners. Twelve male runners (age: 26.1 ± 3.5 years, mass: 66.5 ± 5.6 kg, height 1.79 ± 0.09 m) completed three data collection sessions. Subjects ran six 5-minute trials with 5 minutes of recovery in-between. We tested one velocity per session (12, 14 and 16 km.h^{-1}), at three horizontal impeding force conditions (0, 4 and 8 N). The asymmetries between push and braking duration and effective aerial and contact times were not affected with horizontal impeding forces ($p = 0.265$ and $p = 0.678$, respectively). Vertical force and step length decreased when was applied 8 N of horizontal impeding forces ($p = 0.027$ and $p = 0.019$, respectively). Vertical velocity of the center of mass during downward and upward ratio becomes symmetrical with increase of horizontal impeding forces. With 8 N of horizontal impeding forces the vertical displacement of center of mass during effective aerial downward and upward phases and the vertical displacement of center of mass during effective contact downward and upward phases becomes symmetrical ($p = 0.022$ and $p = 0.017$, respectively). Elastic energy storage decreased with increase of all running velocities ($p = 0.040$) without any effect of horizontal impeding forces ($p = 0.267$). We concluded that horizontal impeding forces can mechanically optimizes the spring mass-model without any changes in landing-takeoff and rebound asymmetries. However, adjustments in vertical forces and step length to minimize the step-average force exerted by the muscle on the ground with increased horizontal impeding forces impair the elastic energy storage into the system.

Keywords: elastic energy; center of mass; drafting; running performance.

KEYPOINTS

- Horizontal impeding forces become the maximal vertical velocity ratio during downward and upward phases symmetrical which optimized the spring-mass model.
- At 8 N of horizontal impeding forces, the vertical displacement of center of mass during effective aerial downward and upward phases and the vertical displacement of center of mass during effective contact downward and upward phases becomes symmetrical.
- Landing-takeoff and rebound asymmetries are not affected by small horizontal impeding forces.
- Vertical forces and step length decrease to minimize the step-average force exerted by the muscle on the ground at 8 N of horizontal impeding forces.

3.1 Introduction

During running on level, the elastic energy is stored and released when muscle-tendon units are stretched (CAVAGNA, SAIBENE and MARGARIA, 1964). During the first half of the contact (t_{brake}), muscles absorb mechanical work (eccentric contraction) and store elastic energy in muscle-tendon units. In the second half of the contact phase (t_{push}), in turn, some part of the elastic energy dissipates as heat, and another part is converted into potential and kinetic energy, adding positive mechanical work (concentric contraction) needed to raise and accelerate the center of mass (BCoM) forward (BLICKHAN, 1989). This elastic energy storage and return occur in elastic tissues such as the Achilles tendon (35% at 16.2 km.h^{-1}), plantar arch of the foot (17% at 16.2 km.h^{-1}) and iliotibial band (14% in comparison to Achilles tendon capacity at 18 km.h^{-1}) (ENG et al., 2015; KER et al., 1987).

Running mechanics has been modeled as a spring-mass system in which the BCoM oscillates on a spring passively with a natural frequency (f_{syst}) with the same height and velocity at landing and take-off (BLICKHAN, 1989; MCMAHON and CHENG, 1990). Cavagna et al. (1988) showed that these assumptions did not hold over a wide range of running speeds. Dividing the step cycle in inferior and superior trajectories of the vertical oscillation of BCoM (s_V), which the vertical force are, respectively, higher and lower than body weight (BW), there are on-off-ground symmetry and asymmetry of the rebound according the running speed. At low speeds, the time of the lower part of the vertical oscillation, t_{ce}, is like that of the superior trajectory, t_{ae} (on-off-ground symmetric rebound). At speeds higher than 11 km.h^{-1}, the t_{ce} turns out lower than t_{ae} resulting in an on-off-ground asymmetric rebound. The vertical displacement of BCoM during effective contact phase (lower part of trajectory), s_{ce}, and step frequency (f_{step}) equals the vertical displacement of BCoM during effective aerial phase (upper part of trajectory), s_{ae}, and f_{syst}, respectively. At high speeds (above 11 km.h^{-1}), these relationships become asymmetrical with s_{ce} and f_{step} lower than s_{ae} and f_{syst}.

Later, Cavagna (2006), besides defining the ratio of t_{ae} and t_{ce} as rebound asymmetry, defined the t_{brake}/t_{push} ratio as landing-takeoff asymmetry in humans and other animals. In the first approach (t_{ae}/t_{ce}), at low speeds, the ratio is symmetrical ($t_{ae} = t_{ce}$) and becomes asymmetrical ($t_{ae} > t_{ce}$) at high speeds due to vertical momentum lost and gained. In the second approach (t_{push}/t_{brake}), at lower speeds, the ratio is asymmetrical ($t_{push} > t_{brake}$), means that forces during t_{brake} are greater than during t_{push}, and at high speeds, the ratio becomes symmetrical ($t_{push} = t_{brake}$) (CAVAGNA, 2006; CAVAGNA, 2009). Additionally, due to gravity and t_{brake}/t_{push}, the maximal vertical velocity of BCoM during downward phase ($v_{v,max,down}$) is higher than the maximal vertical velocity of BCoM during upward phase ($v_{v,max,up}$) (LEGRAMANDI; SCHEPENS and CAVAGNA, 2013). Indeed, recent findings have proved that at high running speeds ($t_{ae} > t_{ce}$ and $t_{push} = t_{brake}$), the elastic mechanism is optimized (MONTE et al., 2020), condition in which $v_{v,max,down}/v_{v,max,up}$ asymmetry becomes symmetrical (CAVAGNA, 2006).

Elastic energy during running historically has been measured for level treadmill running without air resistance. It is reasonable that mechanical work needed to overcome wind at lower velocities (at 10 $km.h^{-1}$) is minimal (MARGARIA, 1968). However, air resistive forces during running become relevant at higher speeds since the drag force varies as the square of velocity (RAYLEIGH, 1876). Elite distance runners sustain a metabolic steady above 20 $km.h^{-1}$ during the marathon (HOOGKAMER, KRAM and ARELLANO, 2017; JONES et al., 2020). At these running speeds, computational fluid dynamics simulations suggest that an elite athlete experiences drag forces of 6.6 N to 7.8 N (1.29 and 1.42% of their BW, respectively) (BEVES and FERGUSON, 2017; POLIDORI et al., 2020). It has been suggested that while running outside, drag forces increase propulsive impulses while braking impulses decrease them (CHANG and KRAM, 1999), however, the elastic energy responses are unclear.

The gold-standard method to evaluate the effect of drag forces experimentally during running is the use of wind tunnels on treadmills (PUGH, 1970; PUGH, 1971; DAVIES, 1980). Alternatively, it possible to compare the effect of drag forces during running comparing treadmill versus overground (BASSETT et al., 1985; JONES and DOUST, 1996; MCMIKEN and DANIELS, 1976) and applying horizontal impeding forces similar to drag forces during treadmill (CHANG and KRAM, 1999; LLOYD and ZACKS, 1972; MESQUITA et al., 2020; ZACKS, 1973). Previous studies with wind tunnel and comparing treadmill versus overground are limited to metabolic cost perspective. However, it was indirectly reported running against air resistive forces, runners leaned their trunk forward, and in some cases, they changed their technique from rearfoot to forefoot strike (DAVIES, 1980; PUGH, 1971). Horizontal impeding forces methods applied heavy external loads ranging 3 to 6% BW at 12 km.h^{-1} (CHANG and KRAM, 1999), and 5, 10 and 15% BW at velocities between 8 and 16 km.h^{-1} (MESQUITA et al., 2020).

Interestingly, there is evidence of "*free-ride*" phenomena (MALOIY et al., 1986) with an increase of external load of 4% BW in the vertical direction of BCoM and saving metabolic energy during running (ABE et al., 2011). In the vertical direction, the vertical load increases the utilization of stored elastic energy by increasing the ratio between negative and positive work activation (with high activation on t_{brake}) of *vastus lateralis* (ABE et al., 2011). For horizontal impeding force, this effect also seems to be confirmed with heavy load (from 10% BW) in the horizontal direction of BCoM (MESQUITA et al., 2020). However, the energy recovery with an increase of horizontal impeding forces is related to energy transduction between potential and kinetic energy (~16% with 15% BW) when the trunk is leaned forward (MESQUITA et al., 2020). The use of horizontal impeding forces similar to drag force in the running would clarify the overground running mechanics.

The purpose of this study was to quantify how small horizontal impeding forces can save energy by spring-mass model and asymmetries of bouncing step (rebound and landing take-off) in long-distance runners. We hypothesized that horizontal impeding forces will affect the four phases of spring-mass model: downward acceleration and deceleration, and upward acceleration and deceleration (CAVAGNA, 2006). Therefore, with an increase of horizontal impeding forces, the spring-mass model will be optimized decreasing the asymmetry between $v_{\text{v,max,down}}/v_{\text{v,max,up}}$, decreasing the asymmetry between s_{ae} during downward and upward ($s_{\text{ae,down}}/s_{\text{ae,up}}$), and increasing the asymmetry between s_{ce} during downward and upward ($s_{\text{ce,down}}/s_{\text{ce,up}}$), becomes all symmetrical. We also expect improvements in spring-mass model will directly translate to the elastic storage with increment in horizontal impeding forces. Finally, the landing-takeoff and rebound asymmetries ($t_{\text{push}}/t_{\text{brake}}$ and $t_{\text{ce}}/t_{\text{ae}}$, respectively) will not be improved with horizontal impeding forces (MESQUITA et al., 2020). Here we expect the small horizontal impeding forces will not heavy enough to affect mechanical at the local level.

3.2 Methods

3.2.1 Participants

Twelve male runners (age: 26.1 ± 3.5 years, mass: 66.5 ± 5.6 kg, height 1.79 ± 0.09 m) participated. They all had recently run a sub-32 minute 10-km race or an equivalent performance in another distance-running event. The study was performed in accordance with the ethical standards of the Declaration of Helsinki. Ethics approval was obtained from the University of Colorado Institutional Review Board (Protocol#18-0110).

3.2.2 Experimental protocol

The study consisted of three data collection sessions. During session 1, the subjects completed a health screening form and signed the informed consent form. During all three sessions, we measured the height, leg length and body weight; thereafter, the subjects warmed-up by running on a custom-built force-instrumented treadmill (KRAM et al., 1998) for 3 min at 3.33 $m.s^{-1}$ (12 $km.h^{-1}$), followed by 3 min at 3.89 $m.s^{-1}$ (14 $km.h^{-1}$). The subjects then ran six 5-minute trials with a 5 min recovery period in between. We tested one velocity per session (3.33, 3.89, or 4.44 $m.s^{-1}$ [16 $km.h^{-1}$]), at three horizontal impeding force conditions (0, 4, and 8 N). The subjects ran with each horizontal impeding force condition twice per visit, in a mirrored order, which was counterbalanced and randomly assigned. We averaged the two values for each condition.

3.2.3 Horizontal impeding forces

To simulate running with air resistance, we applied small horizontal impeding forces at the waist of the runners, near their center of mass (CHANG and KRAM, 1999; LLOYD and ZACKS, 1972). These forces resulted from a hanging mass that was connected via rubber tubing around pulleys to a waist belt. We used long pieces of low-stiffness natural latex rubber to minimize the bouncing of the hanging mass and force fluctuations due to length changes in the rubber tubing from slight anterior-posterior movements of the runner on the treadmill. The rubber tubing was first passed under a low-friction pulley that could be positioned vertically to match the height of the subject’s waist, ensuring that the impeding force was horizontal. The tubing was then attached to an S-beam force transducer (LCCB-50, OMEGA Engineering, INC., Norwalk, CT, USA) which measured the pulling force and fluctuations throughout the running stride. Another piece of rubber tubing was attached to the force transducer and passed over a second low-friction pulley, positioned approximately 6 m high. Hanging masses of 408 and 815 g applied impeding forces of 4 and 8 N, respectively. To counterbalance the weight of the force transducer, we added 305 grams of lead to the hanging mass. The rubber tubing dimensions differed for the two resistive force conditions: for 4 N, we used 3.2/1.2 mm (outer diameter/inner diameter); for 8 N, we used 5.6/1.2 mm. The unstretched lengths of the rubber tubing also differed such that during the running trials, the hanging mass hovered approximately 0.3 m above the floor.

3.2.4 Force measurements

We recorded the vertical (F_z) and anteroposterior (F_y) ground reaction forces and impeding force fluctuations at 1000 Hz sampling frequency for 30 s during the 2nd and 5th minutes using LabView software (National Instruments, Austin, TX, USA). Force traces on LabView were filtered through a forward and reverse low-pass, 4th order Butterworth filter with a cut-off frequency of 30 Hz (DA ROSA et al., 2019). We used the sum of F_z and F_y for the analysis (CAVAGNA, 1975).

3.2.5 Landing-takeoff asymmetries

The signal forces (vertical and anteroposterior) were transformed into acceleration using dynamic general equation of Newton-Euler (acceleration = sum of forces / body mass). The acceleration signals were integrated numerically using the trapezoidal method. The first integration plus the integration constants (average speed in the anteroposterior component and vertical gravitational acceleration) indicated the body speed. This speed curve in its vertical component was integrated again to obtain the vertical position of the body during running (CAVAGNA, 1975).

Twenty steps of each speed were selected for analysis. The brake (t_{brake}) and push (t_{push}) durations were calculated as the time intervals in which the dE_{cm} (t)/dt signals were below (for t_{brake}), and above (for t_{push}) of zero. The time interval where the dE_{cm} (t)/dt signal ~ zero was considered the aerial time (t_a) (CAVAGNA et al., 1988).

3.2.6 Vertical oscillation of the center of mass

Traditionally, step period (T) and vertical oscillation of the center of mass (s_v) during running are divided into their fractions take placing during the contact (t_c and s_c) and aerial times (t_a and s_a). However, considering the spring-mass model acting during running (BLICKHAN, 1989), T and s_v are also divided into their faction in two part: lower and upper parts that depend on equilibrium point (equal to body weight) and vertical force (F_v). A lower part take placing when the F_v is greater than the body weight (t_{ce} and s_{ce}), and when the F_v is lower than body weight (t_{ae} and s_{ae}) at upper part (CAVAGNA et al., 1988). In a total step period was calculated ($T = t_c + t_a$ equal $t_{ce} + t_{ae}$), while a total vertical oscillation of the center of mass ($s_v = s_c + s_a$ equal $s_{ce} + s_{ae}$) were considered in the analysis (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008a). Finally, s_v without effective contact and aerial phase were divided into ascending phase (when BCoM is rising, $s_{ce,up}$ and $s_{ae,up}$) and descending phase (when BCoM is falling, $s_{ce,down}$ and $s_{ae,down}$). Maximal vertical acceleration (a_{vmax}) was calculated as the maximal value during the effective contact phase. The maximal vertical velocity during an upward ($v_{v,max,up}$) and downward ($v_{v,max,down}$) phases of the oscillation were determined as the maximal values in these respective phases (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008b).

3.2.7 Vertical stiffness and system frequency

The mass specific vertical stiffness (k/M$_b$) was calculated as (k/M$_b$ = ($a_{v,max}$ / s_{ce}) where (a_v) is vertical acceleration in m.s^{-2} and s_{ce} is related to vertical displacement of the center of mass during effective contact time from $a_v = 0$ to $a_{v,max}$ (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008). The natural frequency of the spring-mass model was considered as $f_{syst} = 1/\ 2\ (t_{ce})$ equal to (k/M$_b$) $^{0.5}$ / (2T), where T is the step period ($T = t_{ae} + t_{ce}$) (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008). Additionally, we calculated the step frequency f_{step} dividing the T by 1 ($f_{step} = 1 / (t_{ae} + t_{ce})$.

3.2.8 Elastic energy storage

Elastic energy (EL) storage during running (J/kg) was calculated:

$$\mathrm{EL} = \mathrm{F_{max}}\, \Delta \mathrm{S_{ce}} \,/\, 2 \qquad \text{Equation 13}$$

where F_{max} is the peak of vertical ground reaction force during contact (N) and ΔS_{ce} is the vertical displacement BCoM during contact time (m). Therefore, EL value was divided by the step length (m) and body mass (kg) to obtain EL per kg and unit distance ($J.kg^{-1}.m^{-1}$) (CARRARD, FONTANA and MALATESTA, 2018).

3.2.9 Statistics

Data are presented as mean and standard deviation. We performed a two-way ANOVA with repeated measures to compare the effect of running velocity and horizontal impeding force on spring-mass model variables and asymmetries of bouncing step. When significant main or interaction effects were detected, we performed Bonferroni corrected paired t-tests to determine post-hoc which velocity and/or horizontal impeding force comparisons differed significantly. It was adopted for all comparison $\alpha = 0.05$ on Statistical Package for the Social Sciences (SPSS) (IBM Corporation, Inc., New York, United States). Additionally, we calculated partial eta-squared (η^2) to determining the effect size of impeding horizonal force (COHEN, 1973). It was considered the effect size up to 0.020 small, 0.021 to 0.130 medium, and large for value higher than 0.260 (SANTO and DANIEL, 2018).

3.3 Results

Figure 14 shows the effect of running velocity and horizontal impeding force on aerial (t_a) and contact times (t_c), and effective aerial (t_{ae}) and contact times (t_{ce}). The t_a and t_c were both affected with running velocity ($p < 0.001$), but t_a increased while t_c decreased with the increase of all running velocities ($p = 0.007$ and $p < 0.001$; respectively). There was no effect of horizontal impeding forces ($p = 0.217$ and $p = 0.816$), and interaction between running velocity and horizontal impeding force ($p = 0.988$ and $p = 0.718$) for t_a and t_c, respectively.

The t_{ce} was affected with running velocity ($p < 0.001$), without effect of horizontal impeding force ($p = 0.258$) and interaction between running velocity and horizontal impeding force ($p = 0.437$). The t_{ce} values decreased with increase of all running velocities ($p < 0.001$). t_{ae} was not affected with running velocity ($p = 0.091$), horizontal impeding force ($p = 0.200$) and interaction between running velocity and horizontal impeding force ($p = 0.870$) (see Figure 14).

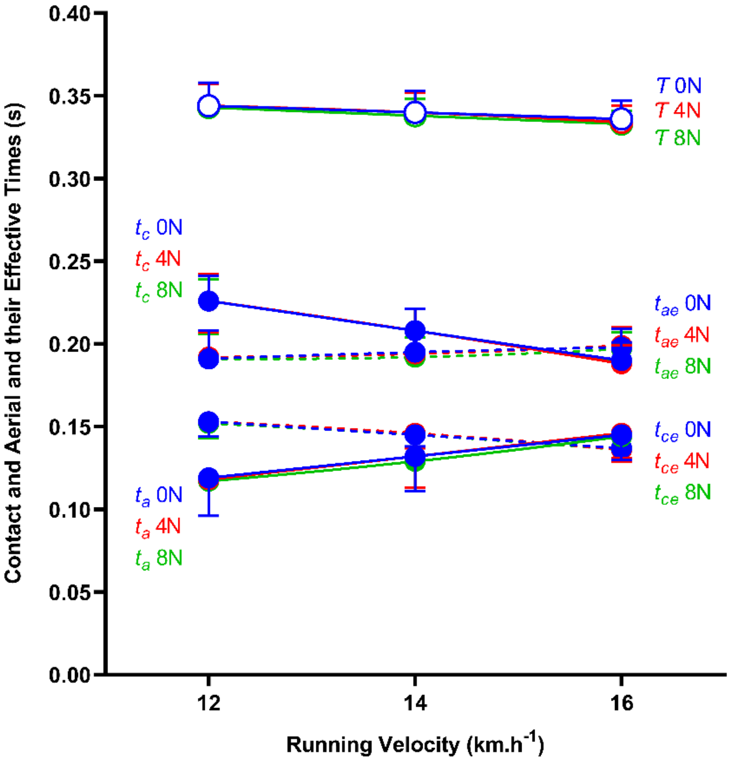

Figure 14. Step period (T), aerial times (t_a), contact times (t_c), effective aerial times (t_{ae}) and effective contact times (t_{ce}) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Open circles with solid lines are related to T. Circles with dashed lines are related to t_{ae} above and t_{ce} below, while circles with solid lines are related to t_c above and t_a below. Blue, red and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively.

The effect of running velocity and horizontal impeding force on the vertical displacement of BCoM (s_v) during contact time (s_c), aerial time (s_a), effective contact time (s_{ce}) and effective aerial time (s_{ae}) are presented in Figure 15.

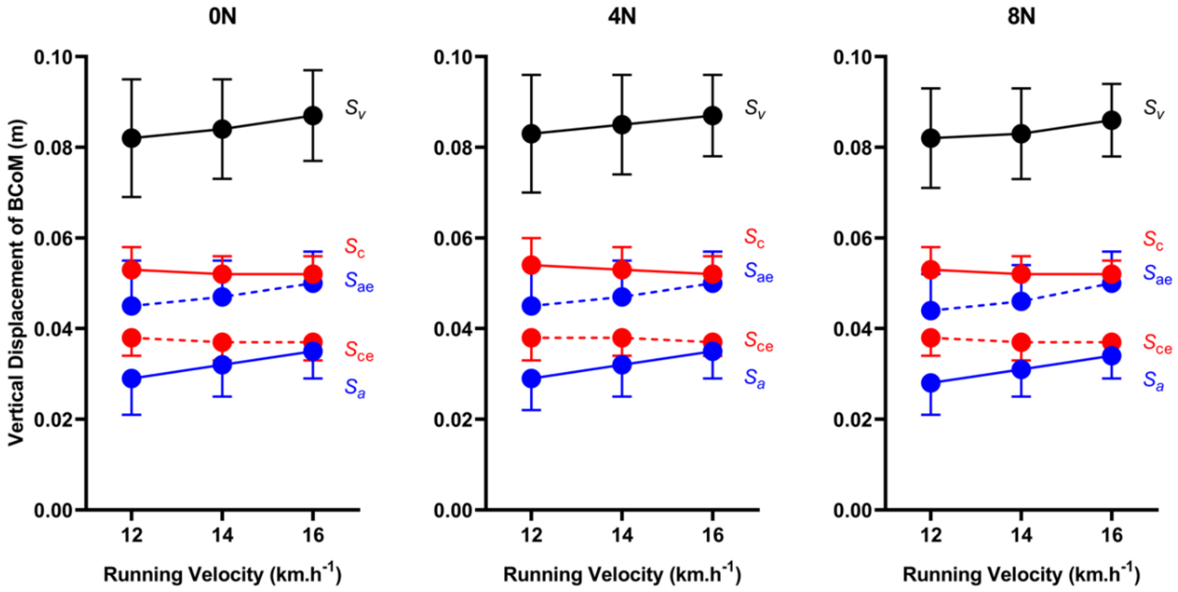

Figure 15. Vertical displacement of BCoM (s_v) during contact time (s_c), aerial time (s_a), effective contact time (s_{ce}) and effective aerial time (s_{ae}) vs. running velocities (12,14 and 16 km.h^{-1}) and horizontal impeding force (0, 4 and 8 N) are presented. Black circles with solid lines are related to vertical displacement of BCoM (s_v), red circles with dashed lines are s_{ce}, red circles with solid lines are s_c, blue circles with dashed lines are s_{ae} and blue circles with solid lines are s_a.

The s_a and s_{ae} values increased with increase of running velocities from 12 to 16 km.h^{-1} ($p = 0.002$ and $p = 0.022$; respectively), and s_a increased with increase of running velocities 14 to 16km.h^{-1} ($p = 0.020$). There was not effect of horizontal impeding force ($p = 0.053$ and $p = 0.126$) and interaction between running velocity and horizontal impeding force ($p = 1.000$ and $p = 0.924$) for s_a and s_{ae}, respectively. Additionally, s_v, s_c and s_{ce} were not affected with running velocity ($p = 0.166$; $p = 0.244$; $p = 0.135$; respectively), horizontal impeding force ($p = 0.122$; $p = 0.286$; $p = 0.226$; respectively) and interaction between running velocity and horizontal impeding force ($p = 0.957$; $p = 0.932$; $p = 0.919$; respectively).

The step length (*L*) values were affected by running velocity ($p < 0.001$) and horizontal impeding forces ($p = 0.009$) (see Figure 3A), without interaction between running velocity and horizontal impeding forces ($p = 0.889$). There was an increase of *L* with increase of all running velocities ($p < 0.001$), whereas *L* decreased 0.8 % with a large effect size ($\eta^2 = 0.347$) when was applied from 0 to 8 N of horizontal impeding force ($p = 0.019$) (see Figure 2A, Appendix S5).

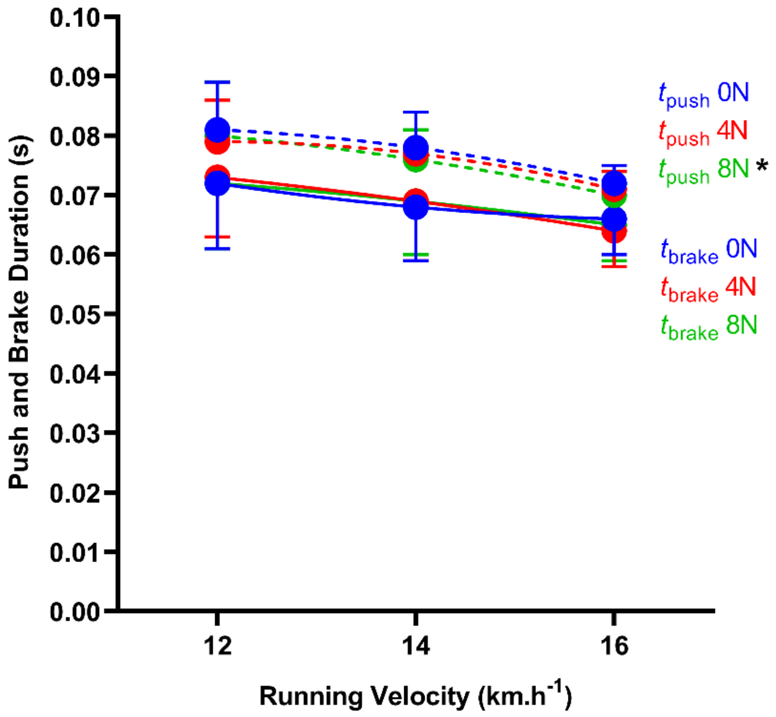

Figure 16. Push (t_{push}) and brake duration (t_{brake}) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Circles with dashed lines are related to t_{push} and circles with solid lines is related to t_{brake}. Blue, red and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively. Symbol (*) represent statistical difference in horizontal impeding force.

The main effect of running velocity and horizontal impeding force on push (t_{push}) and brake duration (t_{brake}) are presented in Figure 16. The t_{push} and t_{brake} were affected with running velocity ($p < 0.001$ and $p = 0.004$; respectively). With increase of running velocities (12 to 16km.h^{-1} and 14 to 16km.h^{-1}; both $p < 0.001$), t_{push} decreased, while t_{brake} also decreased with increase of velocities (12 to 14km.h^{-1}; $p = 0.011$, and 12 to 16km.h^{-1}; $p = 0.015$).

A reduction of 2.6% was observed in t_{push} when was applied 0 to 8 N ($p = 0.047$) with large effect size ($\eta^2 = 0.294$). There was no effect of horizontal impeding force ($p = 0.702$) for t_{brake}, and interaction between running velocity and horizontal impeding force ($p = 0.602$ and $p = 0.181$) for both t_{push} and t_{brake} respectively.

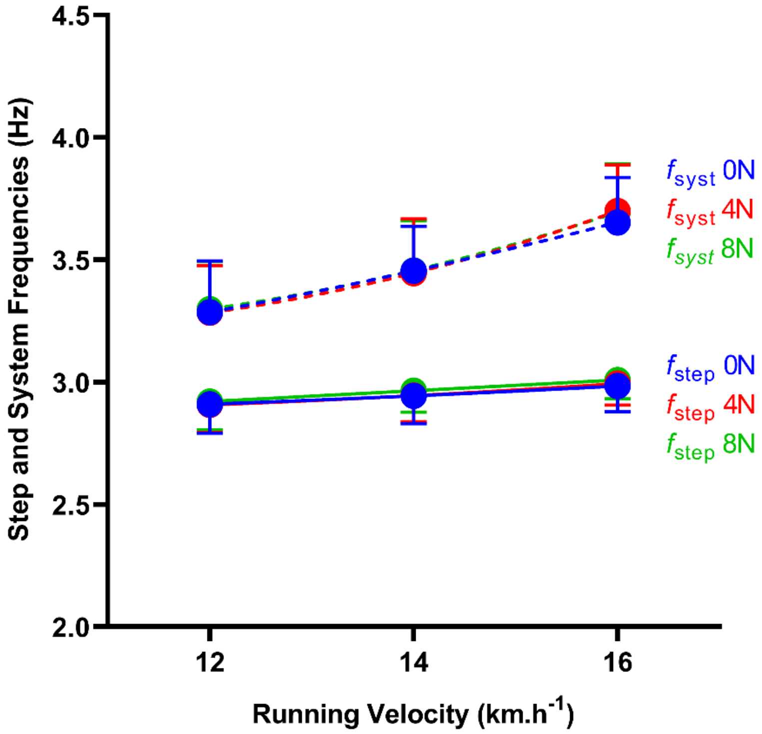

Figure 17. Step frequency (f_{step}) and natural frequency of the system (f_{syst}) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Circles with dashed lines are related to f_{syst} and circles with solid lines are related to f_{syst}. Blue, red and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively.

The step frequency (f_{step}) and natural frequency of the system (f_{syst}) were independent of horizontal impeding force ($p = 0.061$ and $p = 0.223$; respectively) (Figure 17). The f_{step} increased with increase of running velocities 12 to 16 km.h^{-1} ($p = 0.010$), and f_{syst} increased with increase of all running velocities ($p < 0.001$). There was not significant interaction between running velocity and horizontal impeding force for f_{step} and f_{syst} ($p = 0.114$ and $p= 0.329$; respectively).

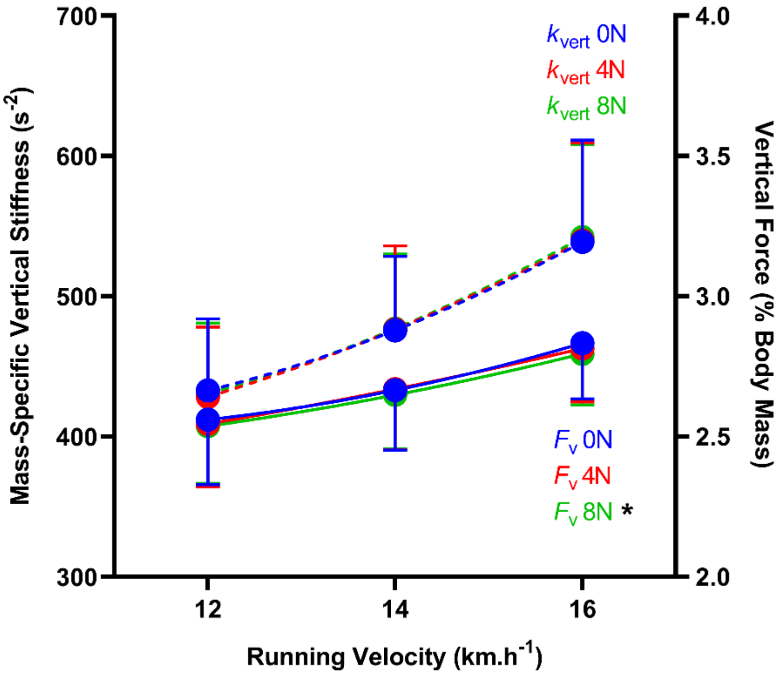

Figure 18. Mass-specific stiffness (k_{vert}) and vertical force (F_v) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Circles with dashed lines and solid lines are related to k_{vert} and F_v, respectively. Blue, red and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively. Symbol (*) represent statistical difference in horizontal impeding force.

There was effect of running velocity on mass-specific stiffness (k_{vert}) and vertical force (F_v) (both $p < 0.001$) (Figure 18). The k_{vert} and F_v values increased with increase of all running velocities ($p < 0.001$ and $p = 0.003$; respectively). In addition, F_v reduced 1 % when was applied 0 to 8 N ($p = 0.027$) with large effect size ($\eta^2 = 0.296$). There was no effect of horizontal impeding force ($p = 0.383$) for k_{vert}, and interaction between running velocity and horizontal impeding force ($p = 0.810$ and $p = 0.701$) for both k_{vert} and F_v, respectively.

In Table 5, asymmetries between maximal vertical velocity during downward and upward phase ($v_{v,max,down}/v_{v,max,up}$), vertical displacement of BCoM during effective aerial downward and upward phases ($s_{ae,down}/s_{ae,up}$), vertical displacement of BCoM during effective contact downward and upward phases ($s_{ce,down}/s_{ce,up}$), effective contact and aerial times (t_{ce}/t_{ae}); push and brake duration (t_{push}/t_{brake}) are described:

Table 5. Asymmetries of bouncing step during running against horizontal impeding forces:

Running Velocity (km.h^{-1})	IHF (N)	$v_{v,max,down}/v_{v,max,up}$	$s_{ae,down}/s_{ae,up}$	$s_{ce,down}/s_{ce,up}$	t_{ce}/t_{ae}	t_{push}/t_{brake}
12	0	**1.065 ± 0.025$^{\#}$**	**1.022 ± 0.062$^{\#}$**	**0.974 ± 0.068$^{\#}$**	1.262 ± 0.177	1.162 ± 0.334
	- 4	**1.062 ± 0.022$^{\#}$**	1.020 ± 0.054	0.977 ± 0.059	1.261 ± 0.156	1.111 ± 0.249
	-8	**1.057 ± 0.022$^{\#}$**	**1.018 ± 0.057$^{\#}$**	**0.979 ± 0.063$^{\#}$**	1.261 ± 0.151	1.152 ± 0.354
14	0	**1.054 ± 0.021$^{\#}$**	**1.043 ± 0.049$^{\#}$**	**0.950 ± 0.056$^{\#}$**	1.350 ± 0.142	1.176 ± 0.244
	- 4	**1.050 ± 0.021$^{\#}$**	1.038 ± 0.051	0.955 ± 0.058	1.343 ± 0.162	1.147 ± 0.259
	- 8	**1.048 ± 0.021$^{\#}$**	**1.036 ± 0.051$^{\#}$**	**0.957 ± 0.057$^{\#}$**	1.333 ± 0.143	1.113 ± 0.221
16	0	**1.044 ± 0.020$^{\#}$**	**1.063 ± 0.042$^{\#}$**	**0.924 ± 0.051$^{\#}$**	1.451 ± 0.127	1.104 ± 0.124
	- 4	**1.043 ± 0.023$^{\#}$**	1.060 ± 0.045	0.928 ± 0.054	1.473 ± 0.133	1.125 ± 0.119
	- 8	**1.041 ± 0.021$^{\#}$**	**1.058 ± 0.042$^{\#}$**	**0.930 ± 0.051$^{\#}$**	1.457 ± 0.133	1.089 ± 0.127

Horizontal impeding force (IHF); asymmetries between maximal vertical velocity during downward and upward phases ($v_{v,max,down}/v_{v,max,up}$); vertical displacement of BCoM during effective aerial downward and upward phases ($s_{ae,down}/s_{ae,up}$), vertical displacement of BCoM during effective contact downward and upward phases ($s_{ce,down}/s_{ce,up}$), effective contact and aerial times (t_{ce}/t_{ae}); push and brake duration (t_{push}/t_{brake}) are presented as mean and standard deviation. Symbol ($^{\#}$) represent statistical difference in horizontal impeding force.

In relation to $v_{v,max,down}/v_{v,max,up}$, $s_{ae,down}/s_{ae,up}$, and $s_{ce,down}/s_{ce,up}$ asymmetries, there was effect of running velocity (all $p < 0.001$), and horizontal impeding force ($p < 0.001$; $p = 0.016$; $p = 0.012$, respectively). There was no interaction effect of running velocity and horizontal impeding force for $v_{v,max,down}/v_{v,max,up}$, $s_{ae,down}/s_{ae,up}$, and $s_{ce,down}/s_{ce,up}$ asymmetries ($p = 0.199$; $p = 0.929$; $p = 0.972$, respectively). The $v_{v,max,down}/v_{v,max,up}$ and $s_{ce,down}/s_{ce,up}$ asymmetries decreased with increase of all running velocities ($p = 0.004$; and $p < 0.001$, respectively) and $s_{ae,down}/s_{ae,up}$ asymmetries increased with increase of all running velocities ($p < 0.001$). The $v_{v,max,down}/v_{v,max,up}$ asymmetry decreased 0.5% when was applied 0 to 8 N ($p = 0.001$) with large effect size ($\eta^2 = 0.578$) and decreased 0.3% when was applied 4 to 8 N ($p = 0.043$) with large effect size ($\eta^2 = 0.578$). The $s_{ce,down}/s_{ce,up}$ asymmetry increased 0.6% when was applied 0 to 8 N ($p = 0.017$) with large effect size ($\eta^2 = 0.332$), and $s_{ae,down}/s_{ae,up}$ asymmetry decreased 0.6% when was applied 0 to 8 N ($p = 0.022$) with large effect size ($\eta^2 =$

0.311). Differences between $v_{v,max,down}$, $v_{v,max,up}$, $s_{ae,down}$, $s_{ae,up}$, $s_{ce,down}$ and $s_{ce,up}$ are reported in detail in Appendix S5.

The t_{ce}/t_{ae} asymmetry was independent of horizontal impeding forces (p = 0.678), but t_{ce}/t_{ae} asymmetry increased with increase of all running velocities (p = 0.012), without significant interaction effect of running velocity and horizontal impeding force (p = 0.634). The t_{push}/t_{brake} asymmetry was not affected with running velocities (p = 0.641), horizontal impeding force (p = 0.265) and interaction between running velocity and horizontal impeding force (p = 0.248).

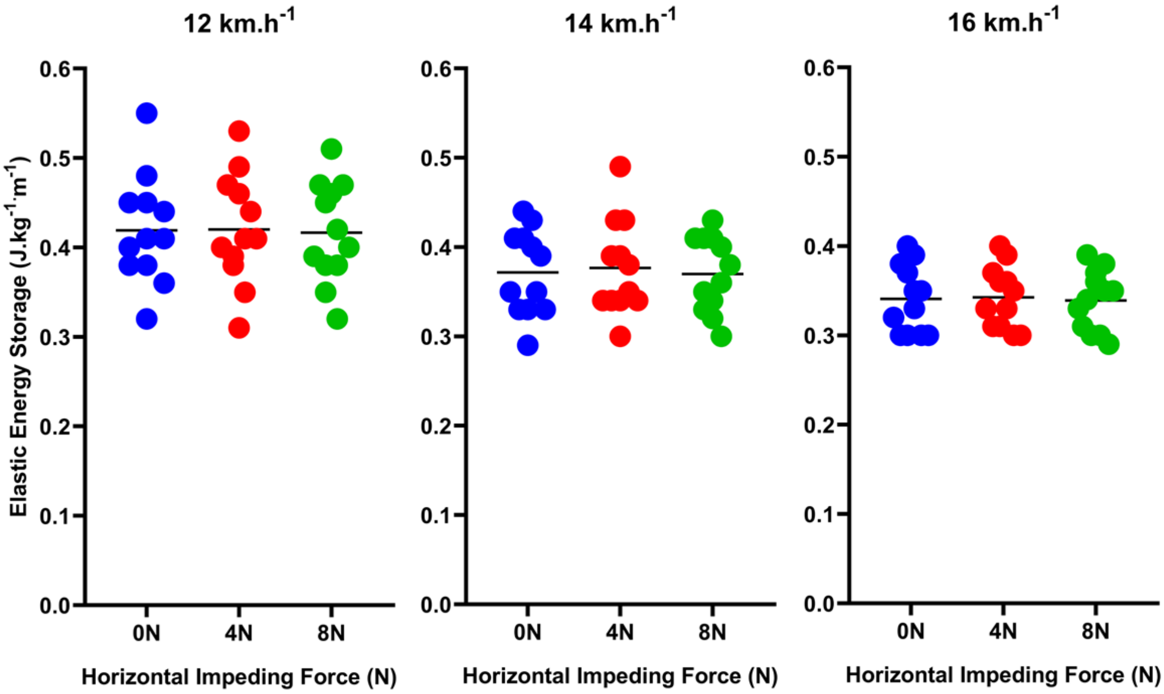

Figure 19. Individual values of elastic energy storage (J.kg^{-1}.m^{-1}) vs. horizontal impeding force (0,4 and 8 N) during different running velocities (12, 14 and 16km.h^{-1}) are illustrated. Blue, red, and green circles are related to horizontal impeding force of 0, 4 and 8 N.

Elastic energy storage decreased with the increase of all running velocities (p = 0.040). However, it was not affected by horizontal impeding force (p = 0.267) and interaction between running velocity and horizontal impeding force (p = 0.967) (Figure 19).

3.4 Discussion

The purpose of the study was to investigate how small horizontal impeding forces can save energy by spring-mass model and asymmetries of bouncing step (rebound and landing take-off) in long-distance runners. Our main results were an overall effect of horizontal impeding forces on spring-mass model variables without changes in t_{ce}/t_{ae} and t_{push}/t_{brake} asymmetries with increased horizontal impeding forces. The $v_{v,max,down}/v_{v,max,up}$ and $s_{ae,down}/s_{ae,up}$ asymmetries decreased, whereas $s_{ce,down}/s_{ce,up}$ asymmetry increased with the increment of horizontal impeding forces in line with our hypothesis that spring-mass would be optimized. However, the improvement of in spring-mass model did not reflect the *EL* with increment in horizontal impeding forces.

Potential and kinetic energies of BCoM during running oscillate in phase during the stride, in which the potential energy in part is transformed to elastic energy during t_a and then it is stored during t_{brake} and released in t_{push} (SAIBENE and MINETTI, 2003). The running velocities above 11 km.h^{-1}, the gravity during s_{ce} increases the vertical velocity of BCoM ($v_{v,max}$) greater than during s_{ae}, reaching maximal values of kinetic energy at $s_{ce,down}$, and becoming this relation asymmetrical ($v_{v,max,down} > v_{v,max,up}$) (CAVAGNA, 2006). It has been demonstrated that in a harmonic elastic system, $v_{v,max,down}$ and $v_{v,max,up}$ oscillate in similar proportions, i.e. representing a ratio of $v_{v,max,down}/v_{v,max,up}$ equal to 1 (CAVAGNA, 2006).

Our results are in line with the assumption there is an asymmetry ($v_{v,max,down} > v_{v,max,up}$) during human running (Table 1) with values higher than 1 at baseline conditions (CAVAGNA, 2006). Also, horizontal impeding forces 0 to 8 N (ratio of 1.054 to 1.049) and 4 and 8 N (ratio of 1.052 to 1.049) were able to decrease the $v_{v,max,down}/v_{v,max,up}$ asymmetries values close to 1, confirming our hypothesis that small horizontal impeding forces could optimize the spring-mass model. Therefore, when the athlete run against external horizontal forces, t_{push} decreases their values close to t_{brake} (Figure 16), when tendon instead muscles sustain the ideally elastic bounce (CAVAGNA, 2009; MONTE et al., 2020), as result, the elastic energy stored during t_{brake} effectively increases $v_{v,max,up}$ assisting BCoM to move forward during t_{push}, since in the second part of contact phase the work is produced against the gravity by muscular contraction when the muscle is shortening and is capable of lower force (LEGRAMANDI; SCHEPENS and CAVAGNA, 2013). In addition, the adjustments in the position of BCoM represented by our symmetrical findings in $s_{ae,down}/s_{ae,up}$ and $s_{ce,down}/s_{ce,up}$ paralleled $v_{v,max}$ changes.

The division of step period into s_{ce} and s_{ae} successfully describes better the elastic system during human running than traditional variables t_c and t_a (BLICKHAN, 1989, DA ROSA et al., 2019). Our results showed that with increasing speed, both t_c and t_{ce} decreased, t_{ae} values were maintained, and t_a increased, resulting in a t_{ce}/t_{ae} ratio asymmetrical (Table 5), however, without significant effect of horizontal impeding forces applied. The effect of running velocity on the asymmetry of rebound is expected in agreement with Cavagna et al. (1988) that showed at running velocities above 11 km.h^{-1} the $t_{ce} < t_{ae}$ and $s_{ce} < s_{ce}$, due to the vertical momentum lost and gained during t_{ce} is greater than t_{ae}. As a result, at high running velocities, there is an increase of vertical acceleration of BCoM greater than 1g during t_{ce} while during t_{ae} it cannot exceed 1g, and therefore longer t_a is needed to counterbalance the momentum gained at t_{ce} (CAVAGNA et al., 1998).

Landing-takeoff and rebound asymmetries (t_{push}/t_{brake} and t_{ce}/t_{ae}) as well t_c and t_a were not affected by the increase of horizontal impeding forces (0 to 8 N). The asymmetries ($t_{push} > t_{brake}$) and ($t_{ae} > t_{ce}$) unchanged with an increase of running speeds. Mesquita et al. (2020) compared the effect of horizontal impeding forces equal to 5, 10 and 15% BW on landing-takeoff and rebound asymmetries in eight recreational runners and found that these asymmetries are harmed with high loads. They found that with the increase of horizontal impeding forces, t_a drastically reduced, and therefore with a short T, t_{ae} also decreases toward t_{ce} (see Figure 20), confirming the energy lost due to gravity during t_a.

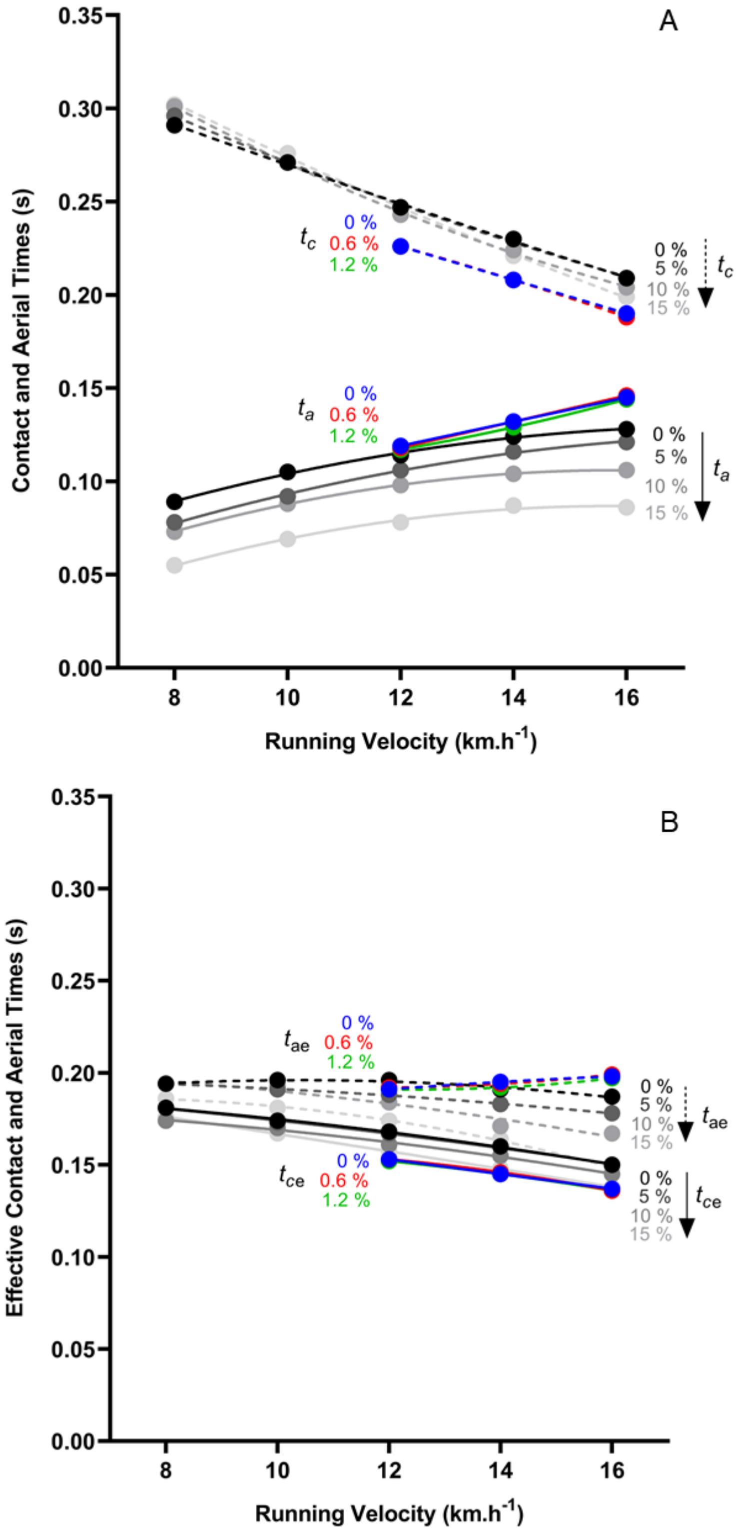

Figure 20. Aerial times (t_a), contact times (t_c) in panel A; and effective aerial (t_{ae}) and effective contact times (t_{ce}) vs. running velocities (12,14 and 16km.h^{-1}) are presented in panel B. Circles with dashed lines are related to t_c in panel A and t_{ce} in panel B, while circles with solid lines are related to t_a in panel A and t_{ae} in panel B. Blue, red and green colors represent the horizontal impeding force of 0, 0.6 and 1.2% of body weight (BW), respectively. Our results were plotted with Mesquita et al. (2020) results that evaluated heavy horizontal impeding forces

corresponding of 0, 5, 10 and 15% BW and represented with black color (baseline or 0% BW), and three more shades of gray for the other conditions (5, 10 and 15% BW).

Regarding the impairment in landing-takeoff asymmetry with high horizontal impeding forces, Mesquita et al. (2020) found an increase in t_{push} and decrease of t_{brake}, which becomes this relation asymmetrical (Figure 21). The $t_{\mathrm{push}}/t_{\mathrm{brake}}$ and $t_{\mathrm{ce}}/t_{\mathrm{ae}}$ findings with high horizontal impeding forces are in line with Dewolf, Peñailillo and Willems (2016) that compared spring-mass model variables during level and uphill running (0 to 9°) on treadmill at running velocities from 5 to 18 km.h^{-1} and found the elastic bouncing $t_{\mathrm{ae}} = t_{\mathrm{ce}}$ and $t_{\mathrm{push}} > t_{\mathrm{brake}}$ with an increase of inclination. It seems that despite of significant decreases t_{push}, in our small horizontal forces (between 0 to 1.2% of BW) were not hard enough to modify those asymmetries.

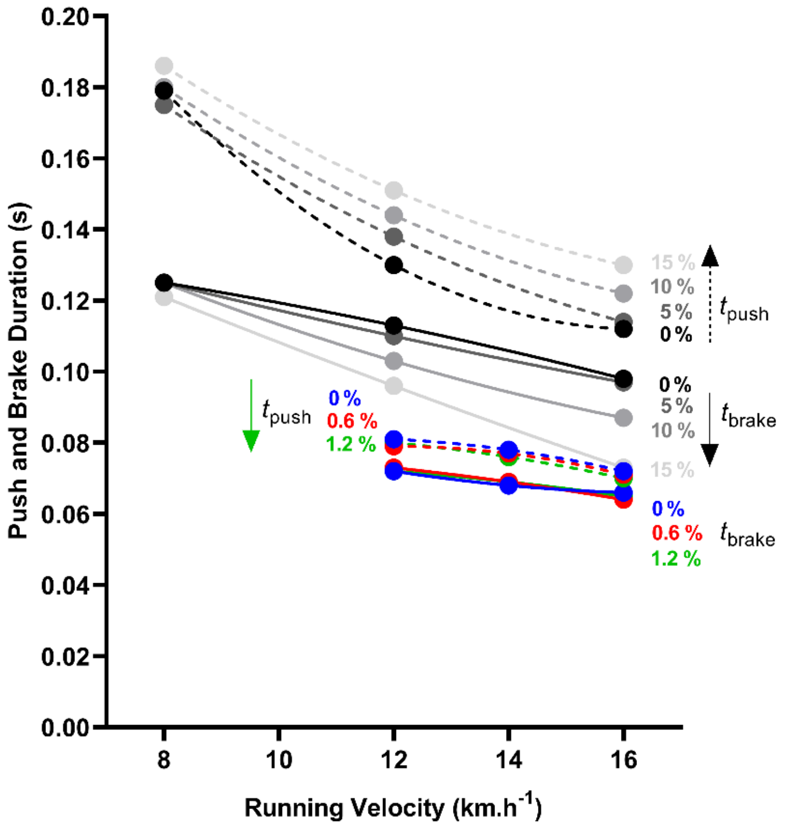

Figure 21. Push (t_{push}) and brake duration (t_{brake}) vs. running velocities (12,14 and 16km.h^{-1}) are presented. Circles with dashed lines are related to t_{push} and circles with solid lines is related to t_{brake}. Blue, red and green colors represent the horizontal impeding force of 0, 0.6 and 1.2% of body weight (BW), respectively. Our results were plotted with Mesquita et al. (2020) results that evaluated heavy horizontal impeding forces corresponding of 0, 5, 10 and 15% BW and represented with black color (baseline or 0% BW), and three more shades of gray for the other conditions (5, 10 and 15% BW).

At low running speeds (up 11 km.h^{-1}), the f_{step} and f_{syst} oscillate symmetrically. Above this speed, both frequencies increase in high running velocities, however, f_{syst} is greater than f_{step} (CAVAGNA et al., 1988). We did not find the effect of horizontal impeding forces on f_{step} and f_{syst} (p = 0.061 and p = 0.223, respectively). Our results regarding the effect of speed are in line with previous studies with young subjects indicating $f_{syst} > f_{step}$ with an increase of running velocity (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008a). This asymmetry between f_{syst} and f_{step} is due to the duration and amplitude of the lower part of vertical oscillation of BCoM are greater than the upper part of vertical oscillation. In this case, the vertical acceleration is greater than 1g, differently from the upper part of the vertical oscillation of BCoM that cannot exceed 1g (CAVAGNA et al., 1991). Old runners with sarcopenia process and lower muscular power in comparison to young runners adopt high f_{step} close to f_{syst} with low vertical oscillation due a t_a (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008), whereas the group low level of training compared to high level of training present low vertical oscillation and t_a and high f_{step} but not associated to f_{syst} (DA ROSA et al., 2019).

The K_{vert} is the ratio of F_v to s_{ce}, increasing due high f_{syst} and reduced t_{ce} with increase of running velocities (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008). We found the effect of running velocity on K_{vert} without effect of horizontal impeding forces. The F_v increased at high velocities, but with 8 N of impeding forces F_v reduces probably due also reduction of L. We suggest here that the reduced F_v applied against air resistive forces could impair the spring-mass compression and low energy is stored (BLICKHAN,1989). It was demonstrated that at 800 m self-paced track running, the running velocity, F_v and K_{vert} drastically decreases between the first 100 to the last 700 m (GIRARD; MILLET; MICALLEF, 2017).

The “free-ride” phenomena related to recovery of energy at running with heavy horizontal impeding forces occurs when the energy of BCoM due to fore-aft movements exchange with vertical movement of BCoM when the period is out of phase. With increase of the work to maintain forward motion of BCoM, the energy transduction can reach 16% at 8 km.h^{-1} when runner horizontal impeding forces of 15% BW (MESQUITA et al., 2020). Contrary to our hypothesis, the improvements in spring-mass model represented by the reduction of t_{push} toward t_{brake} values with 8 N and symmetrical ratios between $v_{v,max,down}/v_{v,max,up}$, $s_{ae,down}/s_{ae,up}$ and $s_{ce,down}/s_{ce,up}$ did not directly translate to *EL.* The *EL* values decreased with the increase of running speeds without any effect of horizontal impeding forces. A possible explanation for the absence of changes in *EL* against horizontal impeding forces could be the fact that *L* values increased significantly with increase of all running speeds (see Appendix S5; Figure 2A).

Interestingly, F_v and *L* both reduced when was applied 8 N. Our runners probably adapted the running technique choosing their *L* close to lower energy expenditure (CAVANAGH and WILLIAMS, 1982). Regarding decreased F_v against 8 N, the vertical force normalized by BW decreased 1.4% from unloaded to 8 N. Our results are in line with Chang and Kram (1999) who found a decrease of 5.4 and 5.8% of F_v when runners performed against horizontal impeding forces of 3 and 6% BW, respectively. We suggest that runners decreased F_v and *L* to minimize the step-average force exerted by the muscle on the ground at 8 N of horizontal impeding forces (CAVAGNA et al., 1991).

Our study has some limitations worthy of mention. Our findings of spring-mass model and bouncing step asymmetries are limited to running speeds up to 16 km.h^{-1}. Future studies should add on horizontal impeding forces methods a kinematic analysis and running speeds above 16 km.h-^{1} to confirm our results and elucidate technique effects such as trunk inclination and changes in rearfoot to forefoot strike (DAVIES, 1980; PUGH, 1971) that can explain the decrease of t_{push} with increase of 8N of horizontal impeding force.

3.5 Conclusion

We concluded that horizontal impeding forces mechanically optimize the spring mass-model without any changes in landing-takeoff and rebound asymmetries. However, adjustments in vertical forces and step length to minimize the step-average force exerted by the muscle on the ground with increased horizontal impeding forces impair the elastic energy storage into the system.

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3.4 Appendix S5

Here we detail the results: 1) Comparison between maximal vertical velocity during downward ($v_{v,max,down}$) and upward ($v_{v,max,up}$) (Figure 1A); 2) Vertical displacement of BCoM during effective aerial time and downward phase ($s_{ae,down}$) and upward phase ($s_{ae,up}$) (Table 1A); 3) Vertical displacement of BCoM during effective contact time and downward phase ($s_{ce,down}$) and upward phase ($s_{ce,up}$) (Table 2A), and 4) The effect of running velocity and horizontal impeding forces on step length (*L*) (Figure 2A).

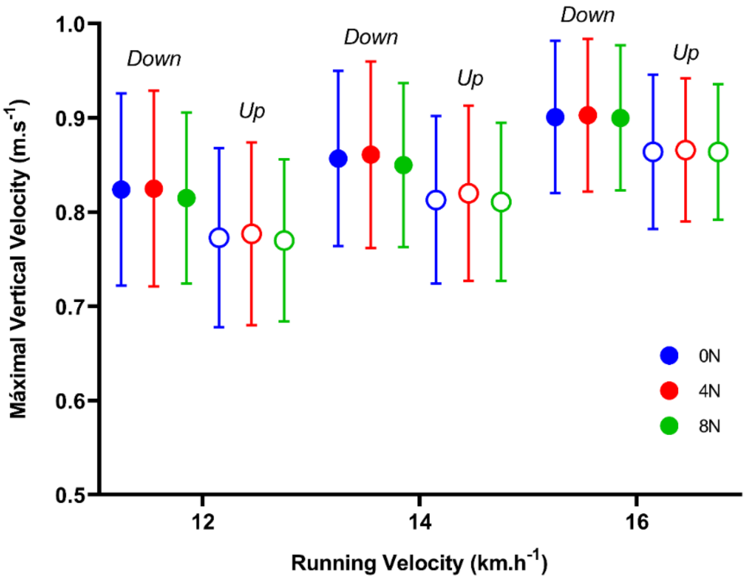

Figure 1A – Maximal vertical velocity during downward ($v_{v,max,down}$) and upward phase ($v_{v,max,up}$) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Filled circles are related to $v_{v,max,down}$ and empty circles with solid lines are related to $v_{v,max,up}$. Blue, red, and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively.

The $v_{v,max,down}$ and $v_{v,max,up}$ are both affected by running velocity ($p < 0.001$). $v_{v,max,down}$ increased with increase of running velocities (12 to 16km.h^{-1}; $p = 0.003$ and 14 to 16km.h^{-1}; $p = 0.027$), while $v_{v,max,up}$ increased with increase running velocities (12 to 16km.h^{-1}; $p = 0.001$ and 14 to 16km.h^{-1}; $p = 0.015$). The $v_{v,max,down}$ and $v_{v,max,up}$ were not affected with horizontal impeding force ($p = 0.225$ and $p = 0.434$, respectively), and interaction between running velocity and horizontal impeding force ($p = 0.940$ and $p = 0.968$, respectively).

Table 1A. Differences between vertical displacement of BCoM during effective aerial downward and upward phases.

Running Velocities (km.h^{-1})	HIF (N)	$s_{ae,up}$ (m)	$s_{ae,down}$ (m)	*p*	Outcome
	0	0.043 ± 0.008	0.045 ± 0.010	0.765	$s_{ae,up} < s_{ae,down}$
12	4	0.044 ± 0.008	0.045 ± 0.009	0.798	$s_{ae,up} < s_{ae,down}$
	8	0.043 ± 0.007	0.044 ± 0.008	0.789	$s_{ae,up} < s_{ae,down}$
	0	0.045 ± 0.007	0.047 ± 0.008	0.496	$s_{ae,up} < s_{ae,down}$
14	4	0.045 ± 0.007	0.047 ± 0.008	0.573	$s_{ae,up} < s_{ae,down}$
	8	0.044 ± 0.007	0.046 ± 0.008	0.535	$s_{ae,up} < s_{ae,down}$
	0	0.047 ± 0.006	0.050 ± 0.007	0.277	$s_{ae,up} < s_{ae,down}$
16	4	0.047 ± 0.006	0.050 ± 0.007	0.322	$s_{ae,up} < s_{ae,down}$
	8	0.047 ± 0.006	0.050 ± 0.007	0.272	$s_{ae,up} < s_{ae,down}$

Vertical displacement of BCoM during effective aerial downward phase ($s_{ae,down}$) and upward phase ($s_{ae,up}$) vs. running velocities (12,14 and 16 km.h^{-1}) and horizontal impeding force (0, 4 and 8 N).

The $s_{ae,down}$ and $s_{ae,up}$ were both affected with running velocities (p = 0.004 and p = 0.031, respectively). Bonferroni post- hoc identified $s_{ae,down}$ increased with increase of running velocity 12 to 16 km.h^{-1}(p = 0.022), however, no effect on $s_{ae,up}$ for all running velocities (12 to 14 km.h^{-1}, p = 1.000; 14 to 16 km.h^{-1}, p = 0.444; 12 to 16 km.h^{-1}, p = 0.615). There was no effect of running velocity for $s_{ce,down}$ and $s_{ce,up}$ (p = 0.135 and p = 0.911, respectively). In addition, there was no effect of horizontal impeding forces for $s_{ce,down}$, $s_{ce,up}$, $s_{ae,down}$ and $s_{ae,up}$ (p = 0.226; p = 0.198; p = 0.126, and p = 0.196, respectively), and interaction effect between running velocity and horizontal impeding forces for $s_{ce,down}$, $s_{ce,up}$, $s_{ae,down}$ and $s_{ae,up}$ (p = 0.919; p = 0.964; p = 0.924, and p = 0.878, respectively).

Table 2A. Differences between vertical displacement of BCoM during effective contact downward and upward phases.

Running Velocities (km.h^{-1})	HIF (N)	$s_{ce,up}$ (m)	$s_{ce,down}$ (m)	*p*	Outcome
	0	0.039 ± 0.005	0.038 ± 0.004	0.527	$s_{ce,up} > s_{ce,down}$
12	4	0.039 ± 0.005	0.038 ± 0.005	0.665	$s_{ce,up} > s_{ce,down}$
	8	0.039 ± 0.004	0.038 ± 0.004	0.628	$s_{ce,up} > s_{ce,down}$
	0	0.039 ± 0.004	0.037 ± 0.004	0.195	$s_{ce,up} > s_{ce,down}$
14	4	0.040 ± 0.004	0.038 ± 0.004	0.332	$s_{ce,up} > s_{ce,down}$
	8	0.039 ± 0.003	0.037 ± 0.004	0.182	$s_{ce,up} > s_{ce,down}$
	0	0.040 ± 0.003	0.037 ± 0.004	0.052	$s_{ce,up} > s_{ce,down}$
16	4	0.040 ± 0.003	0.037 ± 0.003	0.040	$s_{ce,up} = s_{ce,down}$
	8	0.039 ± 0.003	0.037 ± 0.003	0.024	$s_{ce,up} = s_{ce,down}$

Vertical displacement of BCoM during effective contact downward phase ($s_{ce,down}$) and upward phase ($s_{ce,up}$) vs. running velocities (12,14 and 16 km.h^{-1}) and horizontal impeding force (0, 4 and 8 N).

The effect of horizontal impeding forces on *L* across running velocities are presented in Figure 2A:

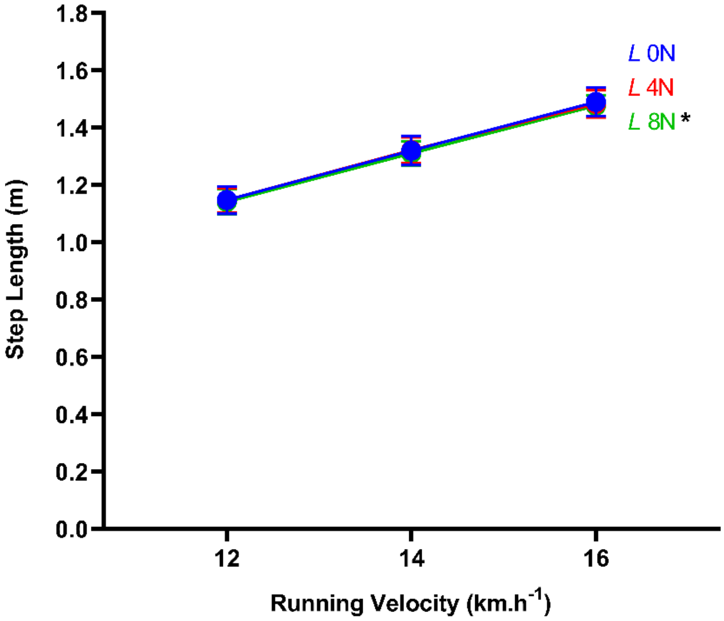

Figure 2A. Step length (*L*) vs. running velocities (12,14 and 16km.h^{-1}) are illustrated. Circles with solid lines is related to L. Blue, red and green circles with solid lines represent the horizontal impeding force of 0, 4 and 8 N, respectively. Symbol (*) represent statistical difference in horizontal impeding force.

CHAPTER 4

INTEGRATIVE ANALYSIS OF RESULTS

4.1 General discussion

The metabolic cost of running in a synergistic task-by-task point of view can be attributed to 80% for body weight support and forward propulsive forces, 7% for leg swing, 2% for lateral balance, however, 11% of total metabolic cost is still unexplained (ARELLANO and KRAM, 2014). Our dissertation results suggest that during running against air resistive forces, the partition those abovementioned more affected is the propulsive forces. The propulsive (I_{prop}) and braking impulses (I_{brake}) are equal and opposite in level running (GOTTSCHALL and KRAM, 2005), but I_{prop} increases while I_{brake} decreases with increments horizontal impeding forces (CHANG and KRAM, 1999). Importantly, our findings show that I_{brake} was not changed according HIF. It has been suggested that metabolic cost of generating horizontal propulsive forces is 1/3 of total metabolic cost (CHANG and KRAM, 1999). We found the metabolic power increased 6.1% per 1% body weight (BW) of horizontal impeding force. Runners in our study who overcame the horizontal impeding forces without reducing their I_{brake} substantially, increased their I_{prop} to a larger extent. Further, there is a negative relation between I_{brake} and I_{prop} (Figure 22). However, we did not found association between changes in metabolic power and changes in I_{prop} ($p = 0.554$) or I_{brake} ($p = 0.640$). Future studies should understand the repercussions of these specific force applications in distance runners.

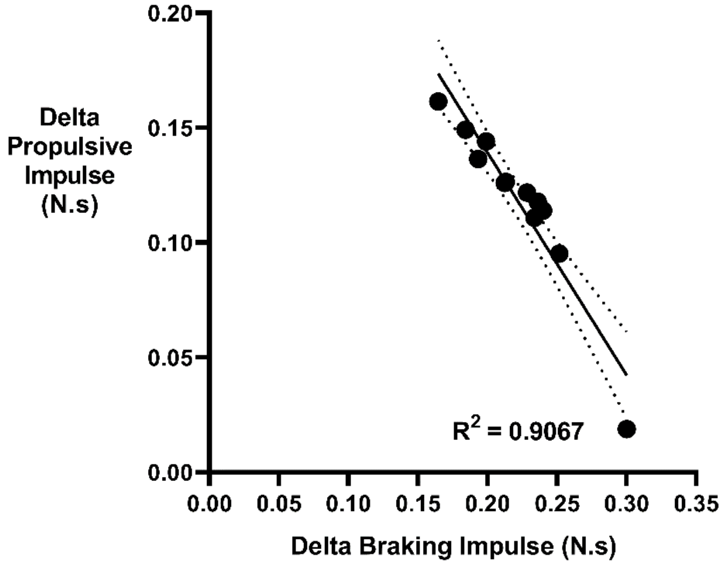

Figure 22. Relationship between delta propulsive and braking impulse ($p < 0.001$).

The increase in metabolic cost associated to aerodynamics drag forces can be also explained to changes muscle efficiency participation during running. According to Alexander (1976) with increase of work associated to drag forces (W_D) during a complete step, the negative work done (eccentric contraction) will decrease $\frac{1}{2}W_D$ and the positive work (concentric contraction) will increase $\frac{1}{2}W_D$. Therefore, runners apply a greater amount of propulsive forces against air resistive forces and these forces are energetically costly due to muscular work and respective muscular efficiency employed.

Other studies estimated the variation of metabolic cost with increase of air resistive forces. Pugh (1970) comparing running versus overground (when wind and running velocity is equal), he found the variation oxygen consumption in $L.min^{-1}$ was dependent of projected frontal area (A_f) in m² and running velocity (v) in $m.s^{-1}$ ($\Delta VO_2 = 0.00354\ A_f\ v^3$). Our method, the hanging masses were applied on the center of mass to know the relation between the increase of metabolic power with increase of horizontal impeding forces expressed relative to % of BW. In our results, the metabolic power varies 6.1% per 1% body weight of horizontal impeding force, but our method is limited to running velocities between 12 to 16 $km.h^{-1}$. Therefore, we combined our results with drag forces calculations and metabolic power extrapolation at running velocities above 16 $km.h^{-1}$ (i.e., drag force of 7.75 N and running velocity of 21.1 $km.h^{-1}$ for Eliud Kipchoge run the marathon in 2-hour), to estimate the energy cost and time saving of drafting strategies. We suggest for the next studies, the improvement of Pugh (1970) cubic equation with our results.

The cost of transport (C) expressed in $J.kg^{-1}.m^{-1}$ represents the energy spent per unit distance covered (SAIBENE and MINETTI, 2003). We combined here the metabolic power and elastic energy storage results from Chapter 2 and 3 to compare the relation between spend and saving energy running against horizontal impeding forces (comparable to air resistance). These integrative results are presented in Figure 23.

The C during level running (~ 4 $J.kg^{-1}.m^{-1}$) are independent of velocity and increases with increase of air resistance forces at high running velocities (DI PRAMPERO, 1986). Here we found values of 3.6, 3.8 and 3.9 $J.kg^{-1}.m^{-1}$ for 12, 14 and

16 km.h^{-1} respectively, on baseline, values of 3.7, 3.9 and 4.0 J.kg^{-1}.m^{-1} for 12, 14 and 16 km.h^{-1} respectively, with 4 N and values of 3.9, 4.0 and 4.2 J.kg^{-1}.m^{-1} for 12, 14 and 16 km.h^{-1} respectively, with 8 N. On baseline, *C* increased with increase of running velocity, contrary the assumption *C* is independent of running velocities. It can be explained in our results because we calculated the metabolic power not extracting the oxygen consumption of resting (SAIBENE and MINETTI, 2003). However, the increases of *C* with increase of horizontal impeding forces agree with previous results showing increments of 9.2% in oxygen consumption for running overground at 21.6 km.h^{-1} in comparison to treadmill (PUGH, 1971).

The elastic energy storage (*EL*) represented 11.7, 9.7 and 8.7% of *C* total during baseline at 12, 14 and 16 km.h^{-1}, respectively. In comparison with horizontal impeding forces conditions, the *EL* represented 11.4, 9.5 and 8.5% of *C* with 4 N at 12, 14 and 16 km.h^{-1}, respectively; and for 8 N of impeding forces, it was 10.8, 9.2 and 7.1% at 12, 14 and 16 km.h^{-1}, respectively. The *EL* was independent of horizontal impeding forces ($p = 0.267$) and decreased with increase of running velocities ($p = 0.040$). As discussed in Chapter 3, reduces of step length (*L*) and vertical forces (F_V) with increases of horizontal impeding forces are strategies to minimize the step-average force exerted by the muscle on the ground and running technique changes to low oxygen consumption at 8 N of horizontal impeding forces (CAVAGNA et al., 1991; CAVANAGH and WILLIAMS, 1982). We suggest the energy cost to overcome propulsive forces are more costly than energies saving due improvements in spring-mass model associated to velocity and displacement of the center of mass.

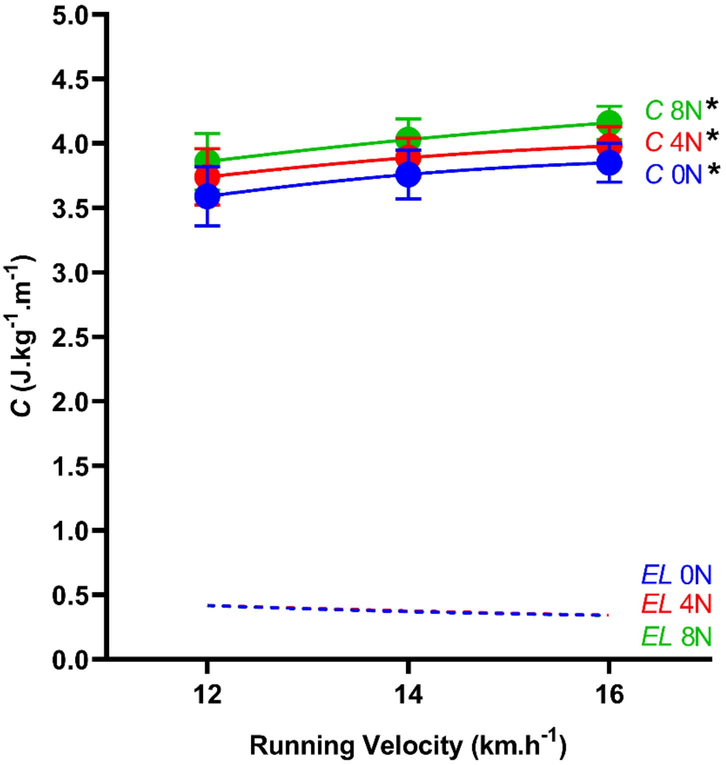

Figure 23. Cost of transport (*C*) and elastic energy storage (*EL*) vs. running velocities (12,14 and 16 km.h^{-1}) are presented. Circles with solid lines are related to *C* and the dashed lines are related to *EL*. Blue, red and green colors represent the horizontal impeding force of 0, 4 and 8 N, respectively. For calculate the *C* (J.kg^{-1}.m^{-1}) we divided the metabolic power data in W/kg (see Chapter 2) by the running velocity in m.s^{-1}. We used the estimated *EL* results from Chapter 3. The *C* was significantly high at fast running velocities ($p < 0.001$), and with large horizontal impeding forces ($p < 0.001$), with a significant interaction effect ($p = 0.026$). The interaction effects were that in response to a specific horizontal impeding force, *C* increased with increasing running velocity (12, 14, and 16 km.h^{-1}; $p < 0.001$) and at a specific velocity, *C* increased with increasing horizontal impeding force [baseline, 4 N, and 8 N ($p < 0.001$)]. The *EL* decreased with increase of all running velocities ($p = 0.040$) and was independent of horizontal impeding forces ($p = 0.267$).

We developed a general model to explain how horizontal impeding forces affect the spring-mass model, the muscle efficiency (eff_{musc}) and running performance using our main results (see Figure 24). Starting from the bottom to top, the horizontal impeding forces (comparable to air resistance) can save (blue lines path) and spend (red lines path) energy at the same time. The influence on each level is describe below:

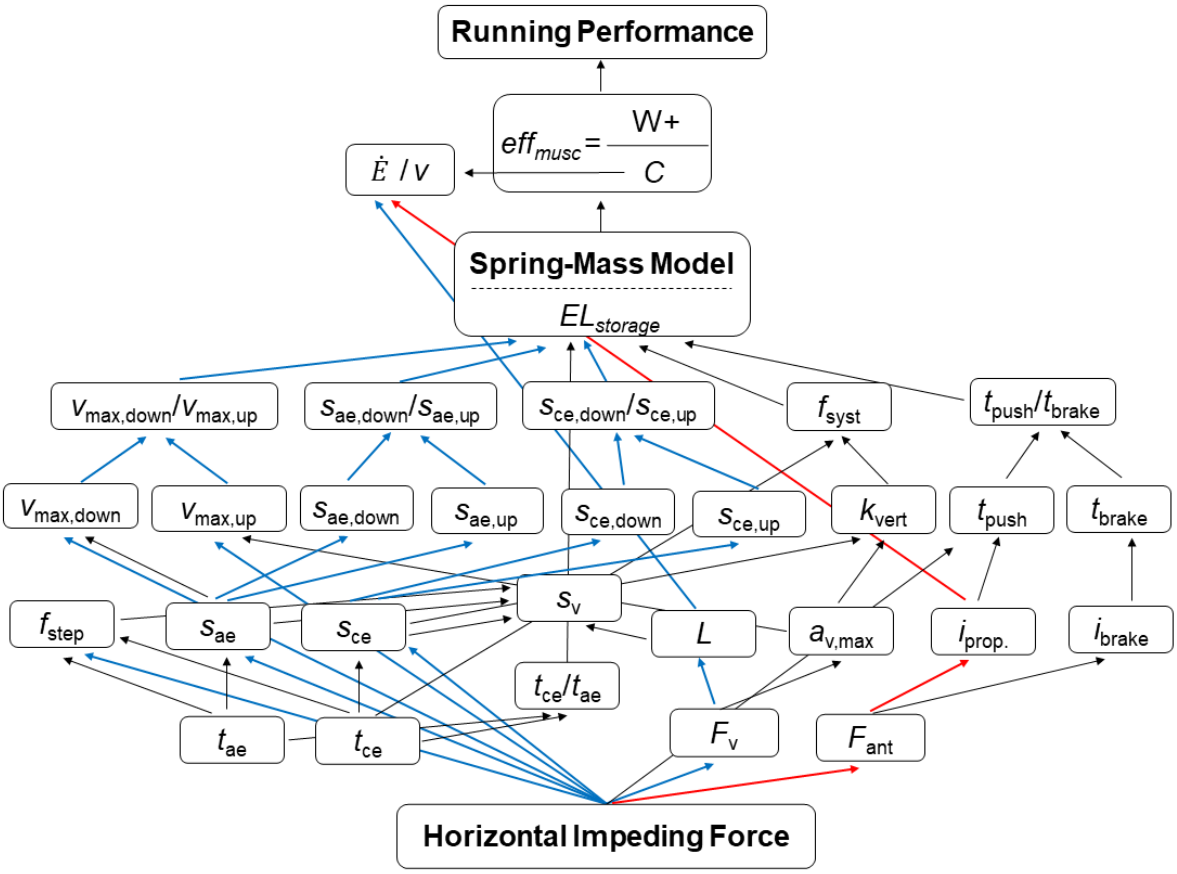

Figure 24. Conceptual model of energy cost to overcome air resistive forces. Asymmetries between effective contact and aerial times (t_{ce}/t_{ae}); push and brake duration (t_{push}/t_{brake}); maximal vertical velocity during downward and upward phase ($v_{v,max,down}/v_{v,max,up}$); vertical displacement of the center of mass during effective contact downward and upward phases ($s_{ce,down}/s_{ce,up}$), and vertical displacement of the center of mass during effective aerial downward and upward phases ($s_{ae,down}/s_{ae,up}$). Cost of transport (C); energy consumption per unit of time ($\dot{E}$); elastic energy storage ($EL_{storage}$); mass-specific stiffness (k_{vert}); maximal vertical acceleration ($a_{v,max}$); maximal vertical velocity during downward ($v_{v,max,down}$) and upward phase ($v_{v,max,up}$); muscle efficiency (eff_{musc}); natural frequency of the system (f_{syst}); positive mechanical work (W+); propulsive (i_{prop}) and braking impulses (i_{brake}); push (t_{push}) and brake duration (t_{brake}); running velocity (v); step frequency (f_{step}); step length (L); vertical (F_v) and anteroposterior forces (F_{ant}). Vertical displacement of the center of mass (s_v) during effective aerial (s_{ae}), contact time (s_{ce}), effective aerial downward phase ($s_{ae,down}$); effective contact downward phase ($s_{ce,down}$). Effective aerial (t_{ae}) and contact times (t_{ce}).

The step frequency (f_{step}) is affected with changes of effective contact (t_{ce}) and aerial times (t_{ae}) ($f_{step} = 1 / (t_{ce} + t_{ae})$), whereas the natural frequency of spring-mass (f_{syst}) is sensitive to changes in t_{ce} ($f_{syst} = 1 / 2t_{ce}$) (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008). The f_{step} and f_{syst} are symmetrical ($f_{step} \sim f_{syst}$) at low and intermediate velocities and becomes asymmetrical at high velocities ($f_{step} < f_{syst}$). We found $f_{step} < f_{syst}$ with increase of running velocities without any effect of horizontal impeding forces. Runners adopted higher f_{syst} than f_{step} increasing their t_{ae} relative to t_{ce} (see Figure 14). Additionally, we suggest that runners adapt the f_{step} (lower than to f_{syst})

reduce the oxygen consumption requirements at high velocities (CAVAGNA et al., 1991). More details about f_{syst} and f_{step} chances are described in Chapter 3.

The L and F_v values reduced with 8 N of horizontal impeding forces. Runners decreases L and exhibit the pattern to minimize the oxygen consumption (CAVANAGH and WILLIAMS, 1982) with increase of impeding forces. The F_v paralleled this change in line with previous studies using 3 and 6% of BW (CHANG and KRAM, 1999). The reduction of F_v can be associated increases of f_{step}.

Total vertical oscillation of the center of mass (s_v) is composed of the sum of vertical oscillation of the center of mass during t_{ce} (s_{ce}) and t_{ae} (s_{ae}) (see all components of s_v in Figure 15). It is expected that s_v and s_{ce} reduces from 10 km.h^{-1}, while s_{ae} remains unchanged with increases of running velocities in young subjects (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008). The s_{ae} increases with increase of running velocities and small horizontal impeding forces does not affect directly s_v or its components. With increment of horizontal impeding forces f_{step} sightly increases and L significantly decreases may cause lower s_v and variation of external energy (CAVAGNA, HEGLUND and WILLEMS, 2005), but we suggest that the increase of s_{ae} can counterbalance s_v expected reductions.

The mass-specific vertical stiffness (k/M_b) is affected by vertical acceleration (a_v) and vertical oscillation of the center of mass during t_{ce} (s_{ce}) since ($k/M_b = (a_{v,max} / s_{ce})^{0.5} / (2 (t_{ce} + t_{ae}))$). The k/M_b increases due high f_{syst} and reduced t_{ce} with increase of running velocities (CAVAGNA, LEGRAMANDI and PEYRÉ-TARTARUGA, 2008) without effect of horizontal impeding forces. The a_v represented by F_v increases at high velocities, but with 8 N of impeding forces reduces F_v due changes of L. We suggest that the F_v reduced against air resistive forces could impair the spring-mass compression and low energy is stored (BLICKHAN,1989), but it is counterbalance with high f_{syst} and low t_{ce} at fast running velocities.

Small horizontal impeding forces improves some asymmetries related velocity and displacement of the center of mass. The asymmetries between maximal velocity of the center of mass during downward and upward ($v_{v,max,down}/v_{v,max,up}$), vertical oscitation of the center of mass during effective contact phase downward and upward ($s_{ce,down}/s_{ce,up}$) and vertical oscitation of the center of mass during effective aerial phase downward and upward ($s_{ae,down}/s_{ae,up}$) becomes symmetrical with increase of horizontal impeding forces, that are close ideal elastic bouncing (CAVAGNA, 2006). However, landing-takeoff ($t_{\text{push}}/t_{\text{brake}}$) and rebound ($t_{\text{ce}}/t_{\text{ae}}$) asymmetries are not affect with horizontal impeding forces (0.6 and 1.2 % BW), in line with previous studies (DEWOLF, PENAILILLO and WILLEMS, 2016; MESQUITA et al., 2020). Here it is possible affirm that improvements on spring-mass model (blue lines path) that could reduce C using mechanical energy are lower than the energy cost to overcome propulsive forces (red lines path) (see Figure 23).

The primary function of muscles during locomotion is produce positive mechanical work (W+, concentric contractions) to move the body forward, but W+ require energy. The ratio between W+ and energy cost (C) needed to produce this mechanical work yields the muscle efficiency (eff_{musc}) (PEYRÉ-TARTARUGA and COERTJENS, 2018). The C during running can be calculated with the energy consumption per unit of time ($\dot{E}$) divided by running velocity (v) (DI PRAMPERO, 1986). These relations are also described in Figure 24.

Our findings of I_{prop} and I_{brake} are in line with Chang and Kram (1999) regarding running against horizontal impeding forces (comparable with air resistive forces), reinforce the propulsive forces requirements at this condition. Alexander (1976) indicated eff_{musc} to overcome W+ against the air resistive forces increases $\frac{1}{2}$, while eff_{musc} related to negative work (W-, eccentric contraction) decreases $\frac{1}{2}$. We suggest that as W+ and C increases with horizontal impeding forces, does not change the eff_{musc}. In Chapter 2, the apparent efficiency was not affected with increase of running velocities and horizontal impeding forces, but apparent efficiency W+ and W- were not analyzed apart. Therefore, for the conceptual model we only considered eff_{musc} being affected with horizontal impeding forces.

Using an optimal drafting a runner with dimensions of Eliud Kipchoge can improve his time at 2-hour marathon in ~4 min (see Chapter 2). According to Kipp, Kram and Hoogkamer (2019) the improvement in time is achieved with increase of v associated to oxygen consumption. If I_{prop} and W+ are reduced with optimal drafting for the same task, the C need to produce mechanical work will decrease ($eff_{musc} = \downarrow \text{W+} / \downarrow C$). Therefore, more energy is available on the system to increase v and running performance ($C = \uparrow \dot{E} / \uparrow v$), in line with Kipp, Kram and Hoogkamer (2019) study.

4.2 General Conclusion

We concluded that spring-mass model can be optimized with high horizontal impeding forces. This optimization is related with increases of high horizontal impeding forces (8 N), becoming the ratio of $s_{\mathrm{ae,down}}/s_{\mathrm{ae,up}}$, $s_{\mathrm{ce,down}}/s_{\mathrm{ce,up}}$ and $v_{\mathrm{v,max,down}}/v_{\mathrm{v,max,up}}$ symmetrical. However, the energy cost to overcome propulsive forces against horizontal impeding forces increases the metabolic cost 6.13% per 1% BW of horizontal impeding force between 12 to 16 km.h^{-1}.

4.3 References

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CHAPTER 5

5.1 The published studies during master's degree

5.1.1 Abstracts presented

MONTEIRO, E. P.; PEYRÉ-TARTARUGA, L. A.; ZANARDI, A. P. J.; SOARES, E.; MORIN, J. B.; PAGNUSSAT, A. S. MOTOR STADIING INFLUENCES SPRINT MECHANICS OF PEOPLE? **V Brazilian Congress of Neurofunctional Physiotherapy and I International Congress of ABRAFIM**, 2018, Florianópolis - SC.

MONTEIRO, E. P.; PEYRÉ-TARTARUGA, L. A..; ZANARDI, A. P. J.; SOARES, E.; MORIN, J. B.; PAGNUSSAT, A. S. Correlation between the elderly age with mechanical variables in sprint. **Physical Activities for the Elderly - SIAFTI, 2018**, Porto Alegre- RS.

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MACHADO, E.; DA SILVA, E. S.; SONDA, F. C. S.; LANFERDINI, F. J.; VAZ, M. A.; PEYRÉ-TARTARUGA L. A. Relação entre arquitetura muscular dos flexores plantares e a potência de saltos verticais. **XVIII Brazilian Congress of Biomechanics and II Latin American Meeting of Biomechanics**, 2019, Manaus-AM.

MACHADO, E.; DA SILVA, E. S.; LANFERDINI, F. J.; PEYRÉ-TARTARUGA L. A. Efeitos da terapia de fotobiomodulação sobre o custo metabólico de corredores fundistas. **II Simpósio de Fisiomecânica da Locomoção Terrestre**, 2019, Florianópolis - SC.

DIAS, J. S. J.; DA SILVA, E. S.; MACHADO, E.; PEYRÉ-TARTARUGA L. A. O tempo de corrida é determinante para o desempenho final em provas de aquathlon. **II Simpósio de Fisiomecânica da Locomoção Terrestre**, 2019, Florianópolis - SC.

DA SILVA, P. R.; DA SILVA, E. S.; GUIMARÃES, P. S.; PEYRÉ-TARTARUGA L. A. Como se comportam as variáveis fisiológicas, antropométricas e biomecânicas de corredores recreacionais? **II Simpósio de Fisiomecânica da Locomoção Terrestre**, 2019, Florianópolis - SC.

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ZANCHI, B., DA SILVA, E. S.; BLOEDOW, L. L. S.; PEYRÉ-TARTARUGA L. A. A percepção subjetiva de esforço no planejamento de treinamento de corredores recreacionais. **II Simpósio de Fisiomecânica da Locomoção Terrestre**, 2019, Florianópolis - SC.

5.1.2 Papers published

BERRIEL, G. P.; COSTA, R. R.; SILVA, E. S.; SCHONS, P.; VARGAS, G. D.; PEYRÉ-TARTARUGA, L. A.; KRUEL, L. F. M. Stress and recovery perception, creatine kinase levels, and performance parameters of male volleyball athletes in a preseason for a championship. **Sports Medicine - Open**, v. 6, n. 1, p. 1-12, 26 June. 2020. http://dx.doi.org/10.1186/s40798-020-00255-w.

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GOMEÑUKA, N. A.; OLIVEIRA, H. B.; SILVA, E. S.; PASSOS-MONTEIRO, E.; ROSA, R. G.; CARVALHO, A. R.; COSTA, R. R.; PAZ, M. C. R.; PELLEGRINI, B.; PEYRÉ-TARTARUGA, L. A. Nordic walking training in elderly, a randomized clinical trial. Part II: biomechanical and metabolic adaptations. **Sports Medicine - Open**, v. 6, n. 1, p. 1-19, 13 Jan. 2020. http://dx.doi.org/10.1186/s40798-019-0228-6.

LANFERDINI, F. J.; SILVA, E. S.; MACHADO, E.; FISCHER, G.; PEYRÉ-TARTARUGA, L. A. Physiological predictors of maximal incremental running performance. **Frontiers in Physiology**, v. 11, p. 1-7, 5 Aug. 2020. http://dx.doi.org/10.3389/fphys.2020.00979.

LANFERDINI, F. J.; SILVA, E. S.; BUENO F. P.; SONDA, F. C.; ROSA, R. G; QUEVEDO, R.; BARONI, B. M.; REISCHAK-OLIVEIRA A.; VAZ, M. A.; PEYRÉ-TARTARUGA, L. A. Effect of photobiomodulation therapy on performance and running economy in runners: a randomized double-blinded placebo-controlled trail. **Journal of Sports Sciences**, Accepted, Jan. 2021.

PASSOS-MONTEIRO, E.; PEYRÉ-TARTARUGA, L. A.; ZANARDI, A. P. J.; SILVA, E. S.; JIMENEZ-REYES, P.; MORIN, J.; PAGNUSSAT, A. S. Sprint exercise for subjects with mild-to-moderate Parkinson's disease: feasibility and biomechanical outputs. **Clinical Biomechanics**, v. 72, p. 69-76, Feb. 2020. http://dx.doi.org/10.1016/j.clinbiomech.2019.11.012.

ZANARDI, A. P. J.; MARTINEZ, F. G.; SILVA, E. S.; CASAL, M. Z.; MARTINS, V. F.; PASSOS-MONTEIRO, E.; HAAS, A. N.; PEYRÉ-TARTARUGA, L. A. Effects of Nordic walking on gait symmetry in mild Parkinson’s disease. **Symmetry**, v. 11, n. 12, p. 1-10, 4 Dec. 2019. http://dx.doi.org/10.3390/sym11121481.

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5.2 Appendix S6

Subject Screening Form
How Do Small Resistive Forces affect the Energetics and Biomechanics of Running?
Investigator: Wouter Hoogkamer, Integrative Physiology Dept.

Name (please print): ____

Date of Birth: Day: _____ Month ______ Year _______

Height _______ Weight ________

1. Describe briefly your typical weekly physical exercise. Indicate approximate duration frequency and intensity. For example: " I run 5 miles, 3 times per week at 7 minute per mile." or "I walk to school every day, about a mile", or "no regular exercise".

____

____

____

____

To the best of your knowledge:

2. Are you in good general health?
Please circle one. yes no

If no, please specify any known problems:

____

____

____

3. Do you have any difficulty with walking, running or mobility in general?
Please circle: yes or no

If yes, please specify: ____

____

____

4. Do you have any problem with balance or dizziness?
Please circle: yes or no

If yes, please specify: ____

5. Do you currently have lingering symptoms or pain related to a serious musculoskeletal injury to your legs, feet, or back?

Please circle: yes or no

If yes, please specify: ____

____

____

6. Have you ever experienced chest pain or shortness of breath with exertion?
It is normal and healthy to breathe rapidly and deeply when exercising intensely. In contrast, “shortness of breath” refers to sudden difficulty with breathing, such as an asthma attack.
Please circle: yes or no

7. Has a doctor told you that you have high blood pressure?
Please circle: yes or no

If yes, please specify: ____

8. Have you ever had a heart attack?
Please circle: yes or no

9. Has a doctor told you that your cholesterol is at a high risk-level?
Please circle: yes or no

10. Do you have diabetes or has a doctor told you that you have pre-diabetes?
Please circle: yes or no

11. Do you have renal (kidney) disease?
Please circle: yes or no

Please sign your name: ____

Today's Date: ______________________

5.3 Appendix S7

Runners needed for Physiology Study

The Locomotion Lab of the Integrative Physiology Department at CU-Boulder is studying how to air drag forces affects the energy cost of running. Our experiments involve running on a force measuring treadmill while small horizontal resistive forces are applied around the waist.

To be eligible, you must be:
- 18+ years old
- In good health
- Able to run 10km in less than 32 minutes

The study consists of up to 3 visit that takes up to 2 hours.

All experiments are completely non-invasive, but you will need to wear a mask that captures your breath. Participants will receive a $25 Amazon gift card per visit.

If you are interested in participating, please contact: curunningstudy@gmail.com

5.3 Appendix S8

University of Colorado
Boulder

Permission to Take Part in a Human Research Study

Title of research study: How Do Small Resistive Forces affect the Energy Cost of Running?
IRB Protocol Number: 18-0023
Investigator: Wouter Hoogkamer, Ph.D.

Purpose of the Study

The purpose of the study is to find out how energy usage (calories) is affected by small resistive forces during running. These resistive forces will be of a similar magnitude as experienced when running outside, or into a slight head wind.

We invite you to take part in this research study because you are a healthy adult runner over the age of 18 and capable of running 10 km in less than 32 minutes.

We expect that you will be in this research study for three visits, each up to 2 hrs.

We expect about 16 people will be in this research study.

Explanation of Procedures

Taking part in this study is completely voluntary. You do not have to participate if you don't want to. You may also leave the study at any time.

Location: University of Colorado Locomotion Laboratory.

During each visit, you will run up to eight 5-minute trials at either 12, 14 or 16 km/h (8:03, 6:54 or 6:02 mile pace), while small resistive forces (up to 3% of body weight) will be applied at your waist.
During the running trials, we will collect and analyze the air you breathe out to calculate the rate at which you burn calories. This involves a mouthpiece, very similar to a SCUBA or skin diving snorkel. You will also wear a nose clip that prevents air from entering or leaving your nose.

Between running trials, you will have a 5-minute breaks, during which the resistive force will be adjusted, using different hanging masses.

Voluntary Participation and Withdrawal

Whether or not you take part in this research is your choice. You can leave the research at any time and it will not be held against you.

You have the right to withdraw your consent or stop participating at any time. You have the right to refuse to answer any question(s) or refuse to participate in any procedure for any reason. Refusing to participate in this study will not result in any penalty or loss of benefits to which you are otherwise entitled.

If you are a CU Boulder student or employee, taking part in this research is not part of your class work or duties. You can refuse to enroll, or withdraw after enrolling at any time, with no effect on your class standing, grades, or job at CU Boulder. You will not be offered or receive any special consideration if you take part in this research.

Risks and Discomforts

The study will take place in the Locomotion Lab, Room 111c Clare Small Building. This room is not open to the general public, but other studies may be taking place in the room while you are taking part in this study. Thus, we cannot assure you of complete privacy because other investigators and their subjects will be able to observe your participation in this study.

There are some potential risks if you choose to take part in this study. These may include: falling on the treadmill, as well as some mild fatigue or soreness. It is important to follow all safety instructions regarding the treadmill. Participating in these experiments does not present any greater cardiac risk than your regular exercise. Nonetheless, if as a direct result of participating in this study, you experience a non-life threatening injury (for example: a cut, scratch or ankle sprain) that requires medical treatment, the experimenters will provide reasonable assistance in getting you to Wardenburg Health Center, or Urgent Care at the Boulder Medical Center. Professor Kram has more than 25 years of experience conducting these sorts of experiments and has never had a subject experience a serious injury.

Fortunately, for an adult without heart disease, who exercises regularly, the risk of a cardiac event (heart attack) during exercise is very small, less than 1 chance in every 400,000 person-hours of exercising (approximately equal to running for 45 years, 24 hours per day). In the unlikely event of a life-threatening event (e.g. cardiac arrest), the investigators would call 911, begin CPR and await EMS arrival. Accordingly, a person trained in CPR will be present during these experiments.

It is important that you tell the Principal Investigator, Wouter Hoogkamer if you think you have been injured as a result of taking part in this study. You can call him/her at 720-526-1552.

Potential Benefits

The direct benefits of being in this study are minimal. You will get a significant amount of vigorous physical exercise. We intend to prepare the results of this study for presentation at scientific conferences and for publication in peer-reviewed journals. In these ways, the study results will be made part of public record and will be made accessible to participants.

Confidentiality

Information obtained about you for this study will be kept confidential to the extent allowed by law. Research information that identifies you may be shared with the University of Colorado Boulder Institutional Review Board (IRB) and others who are responsible for ensuring compliance with laws and regulations related to research, including people on behalf of the Office for Human Research Protections. The information from this research may be published for scientific purposes; however, your identity will not be given out.

We will make every effort to maintain the confidentiality of your data. Confidentiality of personal records will be strictly maintained in all published reports and oral presentations resulting from this study. All participants will be given an alphabetical code as an identifier for the study. Subject information will be kept in locked cabinets in a locked office (Clare Small Building, room 106) under the supervision of Dr. Wouter Hoogkamer. Identifiable data will not be shared with anyone outside of the immediate research team, except as noted below. Data security for storage and transmission for electronic data stored on desktop computers will be managed via a secure network and password access. Power-on passwords will be established for all portable-computing devices.

Payment for Participation

We will give you a $25 Amazon gift card after participating in each visit of this study. If you choose to not finish your participation in the study, we will still give you a $25 gift card for every visit that you attented.
It is important to know that payment for participation is taxable income.

Contact for Future Studies

We would like to keep your contact information on file so we can notify you if we have future research studies we think you may be interested in. This information will be used by only the principal investigator of this study and only for this purpose.
Please initial your choice below:

___ Yes, you may contact me for future research studies. The best way to contact me is: (enter preferred telephone number and/or email address)
____
____

___ No, you may not contact me for future research studies.

Questions

If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team at (303) 492-7984.

This research has been reviewed and approved by an Institutional Review Board (IRB). You may talk to them at (303) 735-3702 or irbadmin@colorado.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.

- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

Signatures
Your signature documents your permission to take part in this research.

Signature of subject Date

Printed name of subject

Signature of person obtaining consent Date

Printed name of person obtaining consent

5.4 Appendix S9

Figure 1A. Running with horizontal impeding forces

Figure 2A. Testing different hanging masses and rubber tubing

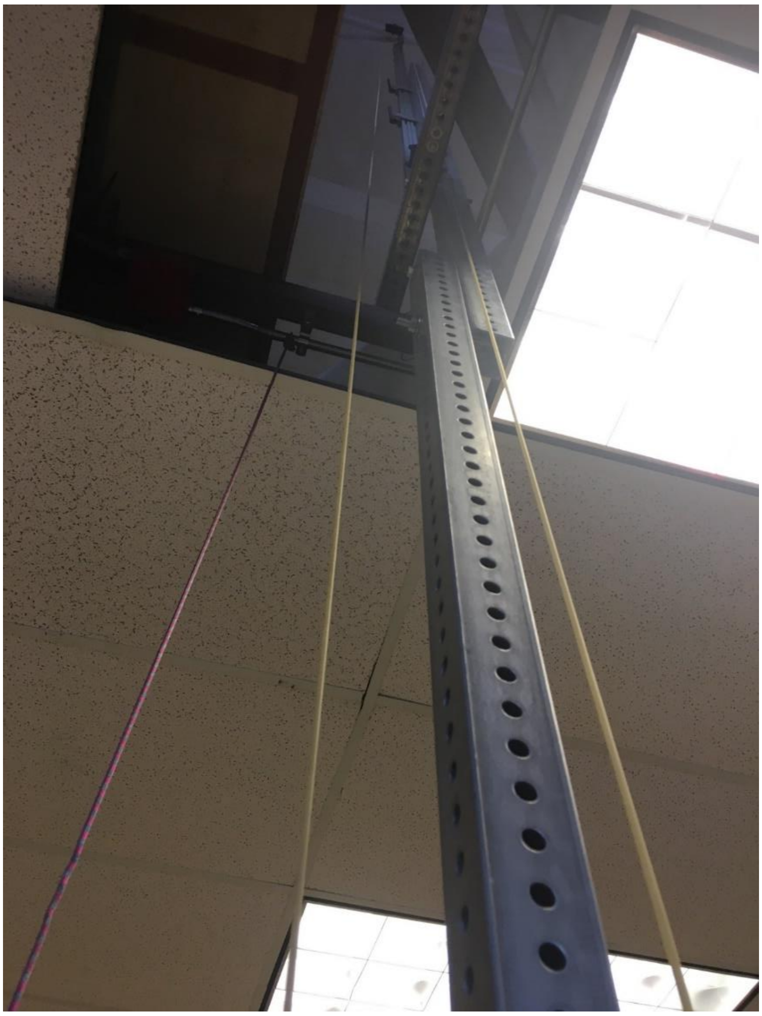

Figure 3A. Building the horizontal impeding force method